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Key Points:

- High-latitude dust sources are located in paraglacial regions ≥50°N and ≥40°S
- Large gaps exist in our understanding of some of the basic characteristics of high-latitude dust sources
- High-latitude sources of dust contribute at least 5% of the global dust budget

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High-latitude dust in the Earth system

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Abstract Natural dust is often associated with hot, subtropical deserts, but significant dust events have been reported from cold, high latitudes. This review synthesizes current understanding of high-latitude (≥50°N and ≥40°S) dust source geography and dynamics and provides a prospectus for future research on the topic. Although the fundamental processes controlling aeolian dust emissions in high latitudes are essentially the same as in temperate regions, there are additional processes specific to or enhanced in cold regions. These include low temperatures, humidity, strong winds, permafrost and niveo-aeolian processes all of which can affect the efficiency of dust emission and distribution of sediments. Dust deposition at high latitudes can provide nutrients to the marine system, specifically by contributing iron to high-nutrient, low-chlorophyll oceans; it also affects ice albedo and melt rates. There have been no attempts to quantify systematically the expanse, characteristics, or dynamics of high-latitude dust sources. To address this, we identify and compare the main sources and drivers of dust emissions in the Northern (Alaska, Canada, Greenland, and Iceland) and Southern (Antarctica, New Zealand, and Patagonia) Hemispheres. The scarcity of year-round observations and limitations of satellite remote sensing data at high latitudes are discussed. It is estimated that under contemporary conditions high-latitude sources cover >500,000 km^2 and contribute at least 80–100 Tg yr^{-1} of dust to the Earth system (~5% of the global dust budget); both are projected to increase under future climate change scenarios.

1. Introduction

Dust has long been recognized as an important component of the lithosphere-atmosphere-ocean system [*Ridgwell*, 2002; *Ravi et al.*, 2011]. Defined here as particles less than 100 μm in diameter, sediments within the dust cycle include those that are entrained, travel within the atmosphere primarily by suspension, and are deposited on land, in lakes, and in the oceans [*Kohfeld and Tegen*, 2007; *Shao et al.*, 2011]. Dust can travel substantial distances from continent to continent and across oceans and affects all of Earth's climatic zones from the tropics to the poles [*Goudie and Middleton*, 2006]. The precise nature of the impact of dust within the atmosphere and following deposition depends on a great extent on particle characteristics such as shape, size, and geochemistry. While these characteristics can undergo some changes during transport, they are primarily determined by the terrestrial source of the sediments and consequently there is a substantial body of research focusing on the sources of dust emissions [*Bullard et al.*, 2011; *Prospero et al.*, 2002; *Washington et al.*, 2003]. To date, this research has predominantly been concentrated on dust sources in the hot, arid, subtropics; however, it is increasingly recognized that dust produced in high latitude and cold environments may extend beyond the local source area and have regional or global significance [*Crusius et al.*, 2011; *Prospero et al.*, 2012; *Anderson et al.*, 2014].

Many of the geophysical processes operating at high latitudes under contemporary environmental conditions are conducive to the production of modern dust, particularly glacial and periglacial processes [*Bullard*, 2013]. However, the magnitude, frequency, and intensity of emissions from high-latitude dust sources have attracted little research attention despite increasing evidence that local and regional high-latitude dust emissions can affect contemporary soil [*Muhs et al.*, 2004], lacustrine [*Mladenov et al.*, 2011], atmospheric [*Johnson et al.*, 2010], marine [*Jickells et al.*, 2005], and cryospheric [*Oerlemans et al.*, 2009] processes as well as contribute to

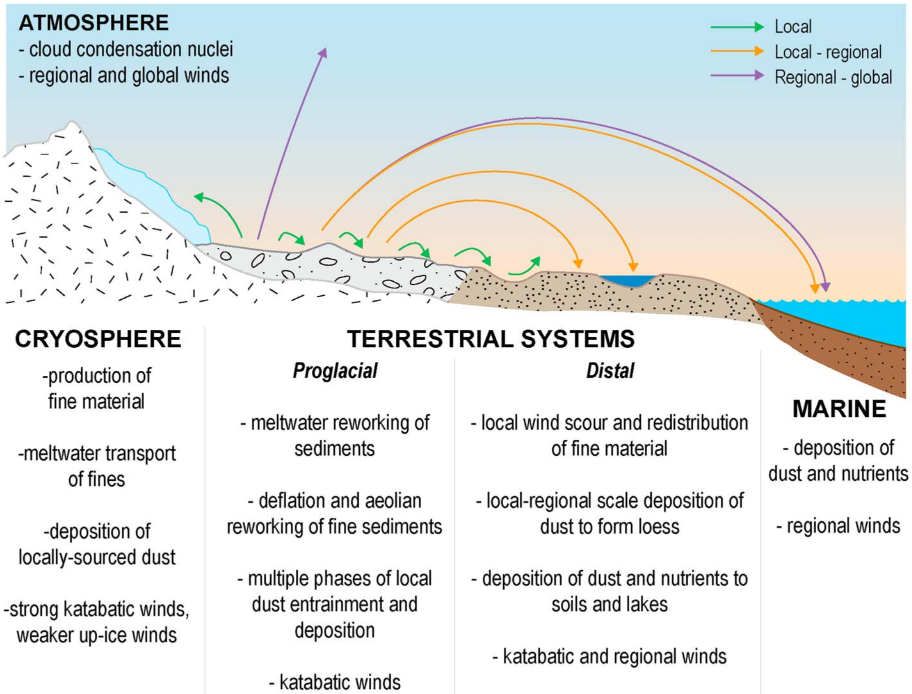

Figure 1. Schematic overview of high-latitude dust sources and sinks in glacial and paraglacial landscapes (inspired by *Anderson* [2007]). See Table 1 for definitions of local, regional, and global.

modern Holocene deposits. Figure 1 is a simplified overview of some of the key high-latitude dust processes operating at local, regional, and global scales. By way of illustration, in New Zealand, dust derived from locally aggrading rivers is calculated to have accumulated at rates of up to 900 $g\,m^{-2}yr^{-1}$ [*Cox et al.*, 1973] forming contemporary loess deposits [*Eden and Hammond*, 2003]. This is higher than most rates of temperate and subtropical dust deposition [*Lawrence and Neff*, 2009] but not uncommon close to sources in high-latitude areas [*Bullard*, 2013]. In recent decades, locally derived dust has been known to impair visibility and degrade air quality in many communities in Alaska, including Anchorage, [*Department of Environmental Conservation*, 2012] and in Reykjavík, the capital city of Iceland [*Thorsteinsson et al.*, 2011].

Many contemporary sources of high-latitude dust are associated with glacial processes. Glaciers are very efficient producers of fine sediment (glacial flour) that is delivered via meltwater to proglacial floodplains. The combination of a continual replenishment of fine material from meltwater floods, limited vegetation cover, and strong ice sheet and/or katabatic winds forms ideal conditions for dust storms. Glacier retreat is expected to expose more land surface area to wind action, and hence, local dust emissions at high latitudes are likely to increase [*Bullard*, 2013]. Around the margins of the major ice sheets, a switch from marine-terminating to land-terminating glaciers could also increase dust source areas. As well as modern proglacial floodplains, paraglacial regions which have been conditioned by glacial activity are also potential dust sources [*Ballantyne*, 2002]. Fragile vegetation cover at high latitudes is vulnerable to the increasing pressures of land use which can cause an increase in dust deflation and wind erosion [e.g., *Sandgren and Fredskild*, 1991].

The aim of this review is to synthesize current understanding of high-latitude dust source geography and dynamics and to provide a prospectus for future research on the topic. The scope of the paper has been restricted in three ways. First, this paper focuses on dust that originates from high latitudes rather than dust that influences these areas but has traveled from elsewhere. Consequently, we do not consider, for example, Asian sources of dust which has traveled to Greenland and been recorded in modern snow pits [*Bory et al.*, 2003a]. Second, the geographical scope is restricted to cold environments located at high latitudes and therefore excludes areas which have cold environments as a result of high altitude. Third, volcanic emissions can contribute substantially to atmospheric dust loading; we do not consider direct

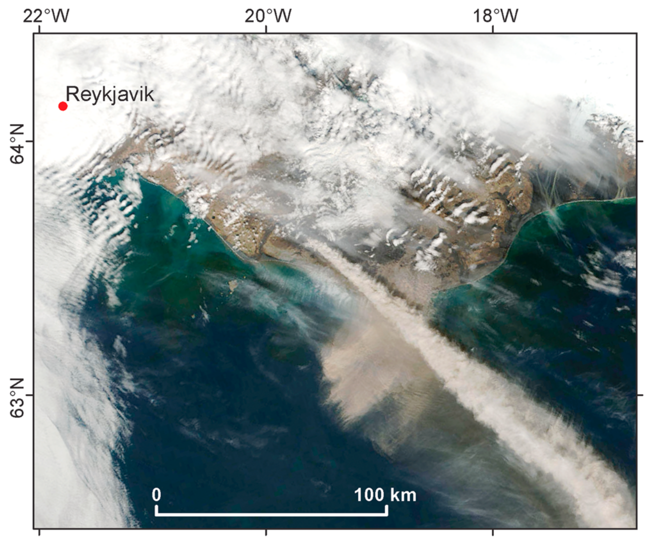

Figure 2. MODIS Terra image 7 May 2010 of southern Iceland showing high-altitude volcanic ash plume from the active Eyjafjallajokull volcano being transported to the southeast and near-surface dust plume of resuspended sediments being blown to the southwest.

volcanic emissions in this paper, however, if volcanic sediments are deposited and subsequently resuspended from high-latitude locations [e.g., *Hadley et al.*, 2004; *Thorsteinsson et al.*, 2012; *Simonella et al.*, 2015], then they are discussed. The temporal scope of the paper is the contemporary period (post-1850 Common Era) [*Masson-Delmotte et al.*, 2013], but we recognize the importance of knowledge gained from Holocene and longer records to our understanding of current and future high-latitude and cold environment dust emissions. At this longer timescale, records of dust deposition at high latitudes extend back over 400 ka and can be found in marine, terrestrial, and ice cores [*Petit et al.*, 1999]. Peak dust deposition is associated with windier and drier climates, particularly those associated with glacial periods [*Fischer et al.*, 2007; *Lamy et al.*, 2014].

Section 2 of this paper considers a definition of modern high-latitude and cold environment dust sources. Section 3 discusses dust-raising processes, highlighting the differences between high-latitude and subtropical dust emission processes and impacts. Section 4 focuses on specific high-latitude regions which are known contemporary dust sources. In the Northern Hemisphere, these are Alaska, Canada, Greenland, and Iceland; in the Southern Hemisphere these are Antarctica, New Zealand, and Patagonia. In each case, the importance of local conditions and drivers that promote dust emissions is highlighted and local impacts documented. The final part of the paper draws on the regional studies to identify the challenges and opportunities for research on high-latitude dust and sets out a research agenda for better understanding of high-latitude dust under recent, contemporary, and future climate scenarios. A glossary is included at the end to aid the reader.

2. Defining High-Latitude and Cold Environment Dust Sources

For the purposes of this paper, "dust" is defined as particles deflated from a surface that travel by suspension in the atmosphere. This may include mineral particles, soil particles, and volcanic ash but does not include direct volcanic emissions during eruptions. To be included in this discussion, the volcanic sediments must have been deposited and then reentrained by the wind (Figure 2). Focusing on the mode of transport—suspension—circumvents the problem of assigning a size range to the sediments in question; sedimentologically, the most common size classes for dust would be silt-sized ($<$63 μm) and clay-sized ($<$4 μm) particles but can also include aggregates of fine particles and sand-sized single particles [*Middleton et al.*, 2001] that are substantially larger than the silt class. The characteristics of dust vary according to the sediments and sedimentary processes operating on the land surface that is the source of the dust particles. The geological substrates in source areas also affect dust composition. In addition to quartz mineral particles, dust can

Table 1. General Physical Characteristics of Aeolian Deposition Based On a Meta-Analysis of 52 Studies [*Lawrence and Neff*, 2009]

Deposition Class	Distance From Source (km)	Deposition Rate g m^{-2} yr^{-1} (mean)	Particle Size % Clay, Silt, and Sand
Local	0–10	50–500 (200)	20, 50, 30
Regional	10–1000	1–50 (20)	25, 60, 15
Global	$>$1000	0–1 (0.4)	30, 70, 0

include feldspars, calcite, halite, and iron- and phosphorus-bearing minerals, as well as organic material such as pollen, diatoms, and bacteria [*Chuvochina et al*., 2011; *Goudie*, 2014]. The framework of *Lawrence and Neff* [2009] to differentiate scales of influence of dust deposits is used here to describe the relationship between the source of the dust and where it is deposited (Table 1). In this, local dust is that which has traveled less than 10 km from source and has a higher proportion of coarse sediments when compared to global dust which has traveled over 10,000 km and is much finer (see also Figure 1).

The major dust sources on Earth have been identified using technologies operated at various scales, ranging from local meteorological stations [*Middleton et al*., 1986] to satellites [e.g., *Prospero et al*., 2002; *Washington et al*., 2003]. Satellite data have the advantage of being available at a near-global scale and collected using uniformity of method, but surveys have primarily focused on the low to middle latitudes. Of the two early global surveys using the Total Ozone Monitoring Spectrometer, *Prospero et al.*'s [2002] dust sources were restricted to lands within 45° north and south of the equator, whereas *Washington et al.*'s [2003] survey extended to 60° latitude north and south. Both studies identified an important "dust belt" in the Northern Hemisphere extending through North Africa, the Middle East, and central and southern Asia and only minor, localized dust sources in the Southern Hemisphere. Some of these Southern Hemisphere dust sources may be included in the scope of high-latitude or cold environment regions. *Ginoux et al.* [2012] mapped global dust sources using the Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue Level 2 product (collection 5.1). This data set is specifically tailored to retrieving data over bright surfaces in the visible spectrum, such as over hot, arid regions, and consequently was unable to be used to identify known dust sources at high latitudes such as in Iceland and Alaska. The study was therefore restricted to latitudes up to 50°N and 55°S (but excluding New Zealand). With the exception of southern South American dust sources, these global overviews have therefore excluded the areas of interest of this paper.

In terms of better defining the geographical extent of this review, the dust source regions of interest can best be described as paraglacial regions at high latitudes. Paraglacial landscapes are those in which nonglacial processes are directly conditioned by glaciation [*Church and Ryder*, 1972]. A key characteristic is a rapid increase in sediment yield in response to glaciation which is followed by a decrease in yield back to predisturbance rates over a relaxation period [*Church and Ryder*, 1972; *Ballantyne*, 2002]. The time during which paraglacial processes occur is spatially variable and controlled not only by large-scale external climate forcing but also by local geological and topographic factors [*Knight and Harrison*, 2009; *Slaymaker*, 2007].

There is no clear definition of "high latitudes." One possible constraint is to include only those areas north or south of the Polar circles (66°33′north and south) which are generally treeless with an annual precipitation less than 500 mm yr^{-1}. This is a very narrow definition and needs to be extended to take into account regional variations in climate and ecology, both of which can affect dust emissions. For example, in the Northern Hemisphere warm ocean currents keep temperatures higher in maritime western Europe compared to the same latitude on the north American coast, which led *Wielgolaski and Inouye* [2003] to define high latitude as greater than 60°N in western Eurasia and greater than 50°N in North America. There are also differences between the Northern and Southern Hemispheres caused by the differential extent and distribution of land masses which would suggest that "high" latitudes in the Southern Hemisphere should start at a lower latitude than in the Northern Hemisphere. However, in terms of dust emissions, compared to the studies of *Prospero et al.* [2002] and *Ginoux et al.* [2012], anywhere poleward of the central global dust belt might be considered high latitude. The working definition for this paper is to consider high latitudes as those areas ≥50°N and ≥40°S.

We are unaware of any existing maps focussing on the locations of high-latitude dust sources. These locations are compiled here from visibility records and known dust observations (Figure 3). The compilation is based on dust storm frequency (DSF) data inferred from meteorological stations recording visibility where a dust storm is defined as an event with visibility <1 km [*Engelstaedter et al*., 2003]. Only those locations where *Engelstaedter et al.* [2003] identified an average annual dust storm frequency of >2 days per year are shown. For stations north of 50°N approximately 25% had a dust storm frequency of 2–10 per year. For southern South America (south of 40°S) local dust storm frequency is higher with three stations averaging 10–50 dust storms per year and eight averaging 2–10. None of the stations used from New Zealand have an annual DSF >2. The visibility data are inevitably patchy due to the sparse distribution of meteorological stations at high latitudes and do not identify some key high-latitude dust sources such as in southern

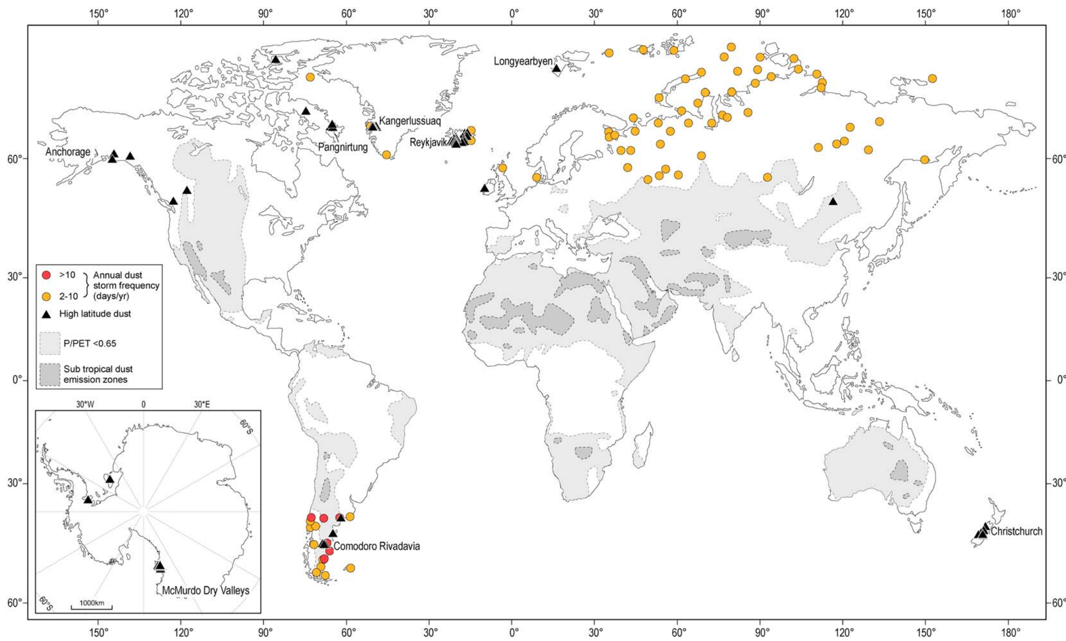

Figure 3. Global observations of high-latitude dust where filled circles indicate dust storm frequency based on visibility data, and black triangles indicate georeferenced published observations of dust storms (see text for details). Areas where the precipitation: potential evapotranspiration ratio <0.65 (aridity index) [*United Nations Environment Programme*, 1997] and subtropical dust emission zones are included for reference.

Iceland. To augment this data set, we have added to the map locations where field and satellite observations of high-latitude dust storms have been made and reported in published academic papers (129 locations reported within 39 different academic papers). We have only included those papers where dust emissions can be attributed to a specific georeferenced location. There is considerable overlap between these areas and cold deserts [*Passarge*, 1921] or Polar deserts which *Péwé* [1974] defines as areas where the mean air temperature of the warmest month is <10°C and mean annual rainfall <250 mm. Globally, areas meeting these climatic criteria cover approximately 5×10^6 km^2 [*Seppälä*, 2004].

3. High-Latitude Dust Entrainment, Transport, and Depositional Effects

The fundamental processes controlling aeolian activity in high latitude, cold environments are essentially the same as in more temperate regions. For a given set of grain characteristics, aeolian sediment transport is positively related to wind velocity and turbulence intensity but negatively related to surface roughness and sediment moisture content [*Bullard*, 2013]. However, there are additional processes specific to cold regions that can modify aeolian transport and the controls on the amount of sediment available, while factors influencing the timing of dust emissions can be substantially different when compared to warm regions [*McKenna Neuman*, 1993; *Bullard*, 2013].

Winds in high latitudes, especially in proximity to ice masses, are some of the strongest recorded on Earth. Long-term global average wind speeds at high latitudes are at least as high as in the subtropics but in some regions, such as Greenland, the coast of Antarctica, Iceland, and southern Patagonia, can be up to 150% higher, 6–8 m s^{-1} compared to 4–5 m s^{-1} [*NASA*, 2014]. The main wind systems driving aeolian sediment transport in high latitudes are frontal and pressure gradient winds, and katabatic and föhn winds [*Wolfe*, 2013; *Bullard*, 2013]. Local breezes can be important where there are strong temperature and pressure gradients over surfaces of contrasting albedo (ice, snow, water bodies, and bare ground). The importance of these varies geographically, and winds associated with the Polar cells differ between Antarctica and the Arctic. The Arctic Basin experiences light winds when the polar cell dominates, but much stronger winds occur when depressions move north from the midlatitudes. For example, winds up to 50 m s^{-1} have been recorded in southeast Greenland [*Hedegaard*, 1982]. In the Antarctic, the high altitude of the continental interior generates strong katabatic winds which can be very persistent. At Port Martin in Antarctica (66°55′S, 141°24′E), thought to be one of the windiest places on Earth, the average annual wind speed is 18 m s^{-1} with individual 24 h averages of $>$29 m s^{-1} and a maximum wind averaged over 2 min of 90 m s^{-1} [*Périard and Pettré*, 1993]. The relative importance of different types of wind systems for mineral aerosol input to the atmosphere globally is poorly constrained [e.g., *Jemmett-Smith et al*., 2015]. By comparison with subtropical dust sources, katabatic winds are likely to be more important for dust transport at high latitudes, whereas dust raising by convective winds is likely to be less important, although local convective dust events such as dust devils have been reported from Canada [*Nickling*, 1978] and Iceland [*Ashwell*, 1986].

Other variables that enhance the ability of the wind to transport sediments at high latitudes are air temperature, air density, and humidity [*Selby et al*., 1974; *Pye*, 1987; *McKenna Neuman*, 1993, 2004]. Colder air is denser than warm air and therefore can exert a higher drag force on particles; this factor suggests that winds in cold environments are more effective at transporting sediment than those in warm environments. *Selby et al.* [1974] suggested that wind speeds of 45 m s^{-1} would be required to entrain a 3 mm (3000 μm) diameter particle to a height of 2 m in a hot desert, while speeds of 36 m s^{-1} could achieve the same in a cold desert at −70°C. *McKenna Neuman* [2003] found that for the same wind speed the quantity of sand transported could be as much as 70% higher at temperatures of −40°C compared with temperatures of +40°C. This increase is attributed in part to greater air density and turbulence intensity associated with cold air masses, although McKenna Neuman suggests that reduced interparticle cohesion associated with exceptionally low absolute humidity likely plays the primary role. *McConnell et al.*'s [2007] analysis of dust in an Antarctic ice core suggests dust deposition increases with decreasing relative humidity. There have been some observations of a strong inverse relationship between relative humidity and dust emissions at the individual event scale, but this needs further exploration. In cold environments the saltation cloud can be deeper and comprises coarser particles than in warm environments presumably due to the enhanced fluid stress and large coefficient of restitution associated with particle rebound on surfaces indurated with pore ice [*McKenna Neuman*, 1993]. The majority of studies of particle transport at low temperatures have focused on the aeolian transport of sand-sized particles, and there are no comparable measurements for silts and clays. However, given that saltation-impact entrainment ("sand-blasting") [*Shao et al*., 1993] of fine particles by coarser particles is the dominant driver of all aeolian transport, including suspension, this enhanced sand transport capacity is also likely to be important for dust emissions [*Bullard*, 2013]. Indeed, frozen sediments become increasingly brittle with a drop in temperature below the freezing point and may fracture under particle impact creating finer particles, but little experimental work has been carried out in regard to this proposed mechanism for dust generation.

Although precipitation (whether rain or snow) can be very low ($<$500 mm), high-latitude dust source areas are not typically classified as arid due to the very low corresponding rates of evaporation (Figure 3). In fact, some key dust source areas at high latitudes have very high annual rainfall amounts; e.g., southern Iceland receives on average $>$1500 mm yr^{-1} [*Crochet et al*., 2007]. The amount of soil moisture required to prevent aeolian sediment transport has been the subject of considerable research and varies from $<$5% to 25% but is typically suggested to be at the lower end of this range [*McKenna Neuman and Nickling*, 1989; *Wiggs et al*., 2004]. Grain characteristics affect the moisture-holding capacity of sediments, but often, the effect of moisture is short lived in hot deserts because it is quickly evaporated by high temperatures; in cold deserts, strong winds can rapidly desiccate the surface allowing the upper most particles to be entrained. Even during rain events, dust storms have been recorded at high latitudes. *Ashwell and Hannell* [1960] observed dust storms occurring during light rain and drizzle with winds of 6 m s^{-1} in Iceland. In heavier rain, splash detachment of particles can increase the amount of material in aeolian transport by ejecting fine particles into strong air streams [*Marzen et al*., 2015]. Rain is often assumed to wash dust out of the atmosphere, but with strong winds this is not always the case; for example, a dust storm in 2014 on the mainland of Iceland that occurred during rain was recorded in a dust sampler on Heimaey, an island 17 km offshore (J. Prospero, personal communication).

Where the mean annual temperature is at or below −9°C, permafrost (permanently frozen ground) can exist. In these areas, the ground is completely frozen in winter and this can substantially reduce aeolian sediment transport as any pore ice present will cement the mineral particles together increasing the threshold velocity required for entrainment. Sublimation, rather than evaporation, is reported to play an important role in particle release under winter conditions, while these particles may further abrade the surface during saltation transport, thereby ejecting additional sediment into the particle cloud [*McKenna Neuman*, 1993]. Similar

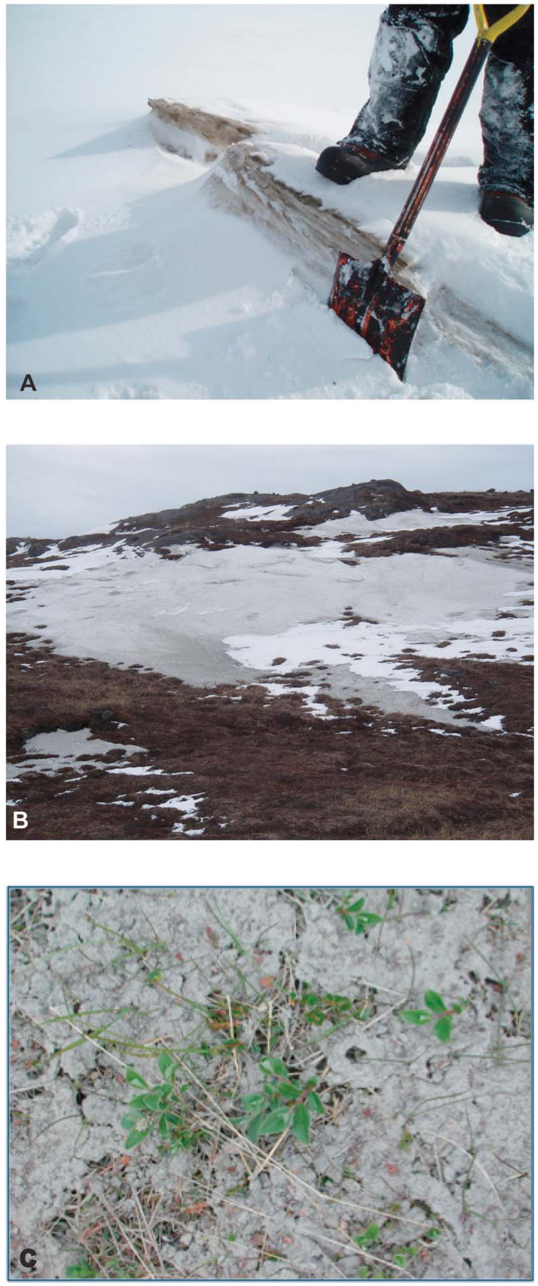

Figure 4. (a) Dust layers in sea ice, McMurdo Sound, Antarctica. Photograph courtesy of Cliff Atkins. (b) Layer of dust on seasonal snow in southwest Greenland. (c) Dust deposit remaining on top of vegetation following snowmelt in southwest Greenland. Photographs in Figures 4b and 4c courtesy of John Anderson.

processes also occur in seasonally cold regions in the absence of permafrost. In permafrost areas during the warmer summer months, a relatively thin active layer develops at the surface in which the temperature remains above the freezing point. This layer, however, tends to retain a large amount of water throughout the season because of the low permeability associated with pore and segregated ice often found within the permafrost table below. This retained water may support the growth of a low and often sparse vegetation canopy which shelters the surface from the fluid drag of the wind and thereby deflation.

When vegetation is viewed as a roughness element [e.g., *Webb et al*., 2014], its effects on dust processes are the same at high latitudes as in the subtropics. These effects typically cause an increase in the threshold for particle entrainment decreasing potential emissions [*Wolfe and Nickling*, 1993] and can also promote dust deposition through trapping particles on leaves and stems [e.g., *Hope et al*., 1991]. The main difference, which is especially important for year-round studies, is that the growing season in high latitudes can be very short but vigorous. This means that the moderation of threshold wind speed by vegetation may be seasonally very variable. At a larger spatial scale, vegetation density and height generally decreases with latitude. The main biomes at high latitudes are grasslands, taiga (boreal coniferous forest), and tundra (restricted tree growth, low growing mosses, shrubs, and lichens) with low species diversity. On newly exposed sediments around the margin of ice sheets and glaciers there is a complex array of factors affecting the rate of soil development and vegetation succession [*Matthews*, 1992]. Initially, the surface is unvegetated, but vegetation gradually and slowly starts to establish with biological soil crusts, mosses, and lichens. This process can be as slow as <5% cover in one to five decades [*Tisdale et al*., 1966; *Cannone et al*., 2008] thereby providing little protection against deflation. Combined, the variability of these atmospheric, soil, and vegetation characteristics means that determining the threshold for particle entrainment in cold environments can be more complex at both the event and seasonal timescales than in the subtropics [*Barchyn and Hugenholtz*, 2012].

A particular characteristic of high-latitude, cold environment dust regions is the development of niveo-aeolian deposits. These are intercalated deposits of wind-blown snow and sediments. Most research has focused on landforms or stratigraphic signatures created when sand and snow have interacted and the snow melts (denivation) [e.g., *Koster and Dijkmans*, 1988], but blown dust in cold environments can accumulate on top of the snow pack or in layers within in it (Figure 4). For example, multiple layers of snow or ice and fine sediments have been reported from multiyear sea ice in Antarctica [*Atkins and Dunbar*, 2009; *Miller et al*., 2015]. The accumulation of dust in snow layers during a winter season can also cause pulses of fine sediment to be input to soils and lakes when the snow melts. This may affect terrestrial processes by smothering vegetation causing death or a decrease in biodiversity, as observed on Ellesmere Island by *Edlund and Woo* [1992], and can affect freshwater systems, for example, by causing pulses of nutrient input to lakes [*Mladenov et al*., 2012]. In areas of patchy snow cover, wind erosion of sediments from exposed soils can accumulate in snow patches as niveo-aeolian deposits, and the local rate of accumulation can exceed rates of soil loss by runoff [*Lewkowicz and Kokelj*, 2002].

As in the subtropics, dust emissions at high latitudes can be increased by anthropogenic activities that disturb or expose land surfaces. Such activities include mining [*Dörnbrack et al*., 2010], transportation [*Myers-Smith et al*., 2006], agricultural activities, including ploughing and grazing [*Arnalds and Barkarsson*, 2003], deforestation [*Arnalds*, 1987], and altering the hydrological regimes of rivers [*Vilmundardóttir et al*., 2010]. Equally, appropriate land management practices can reduce dust emissions [e.g., *Gao et al*., 2014].

Globally, dust has an impact on every aspect of the lithosphere-atmosphere-ocean system [*Ravi et al*., 2011]. These impacts have been widely reviewed in the context of the Earth system overall [e.g., *Carslaw et al*., 2010; *Maher et al*., 2010; *Shao et al*., 2011] and from a range of specific perspectives such as the impact on the atmosphere [e.g., *Choobari et al*., 2014], biosphere [*Ravi et al*., 2011], cryosphere [*Cook et al*., 2016], and human health [*Goudie*, 2014]. Although these reviews primarily focus on low-latitude dust, many of the broad impacts are similar for high latitude dust. We highlight here only two areas of recent focus where the deposition of dust from high-latitude sources has the potential to have substantial effects. These are (i) as a nutrient source to the marine system and (ii) in its impact on snow/ice albedo.

Iron was first suggested to limit the growth of phytoplankton in certain parts of the ocean by John Martin [*Martin and Fitzwater*, 1988]. *Martin* [1990] hypothesized that the high concentrations of dust observed in Antarctic ice core sections from the Last Glacial Maximum (LGM) ~20,000 years ago were evidence that the dust flux to the ocean was higher at that time than during the most recent 10,000 years. This dust flux supplied iron to the ocean, fueling higher primary productivity, lowering surface ocean pCO_2, and thereby reducing the concentration of CO_2 in the atmosphere from 280 ppmv during interglacial periods to 190 ppmv during glacial periods. Experiments were subsequently performed confirming iron limitation in the Equatorial Pacific [*Martin et al*., 1994], the Southern Ocean [*Coale et al*., 2004], and the subarctic North Pacific [*Boyd et al*., 2004]. These regions are often referred to as “high-nutrient, low-chlorophyll” (HNLC) regions, because they contain abundant supply of the macronutrient nitrate, yet maintain low-chlorophyll concentrations. This combination hints that low biological productivity is maintained in these waters because they are situated far from the largely terrestrial iron sources. Note that many of the HNLC regions of the ocean are located at high latitudes (including parts of the North Atlantic) [*Nielsdóttir et al*., 2009]. Recently, marine sediment core records from the Southern Ocean revealed both high productivity and high dust flux during the LGM [*Martínez-García et al*., 2014], consistent with Martin’s original hypothesis.

Despite their proximity to several HNLC regions of the ocean, high-latitude dust sources have largely been overlooked in global compilations of dust flux [*Mahowald et al*., 2009; *Shao et al*., 2011], which tend to emphasize the well-studied large fluxes from subtropical deserts. This reflects a dearth of observations at high latitudes more than any explicit suggestion that high latitudes are unimportant sources. High-latitude dust was first suggested as a possible source of iron to the subarctic North Pacific by *Boyd et al.* [1998]. Yet only recently did *Crusius et al.* [2011] document the first observations of widespread dust from southern Alaska. Modern-day observations of dust in high latitudes remain rare, as do observations of dust transport from other locations to the high latitudes.

It is worth noting that at high latitudes, light levels impact primary productivity, not just nutrients. This means that a high dust flux to these regions of the ocean might not directly result in increased productivity if the high dust flux occurs at a time of low light levels. As an example, the dust flux from the southern Alaska

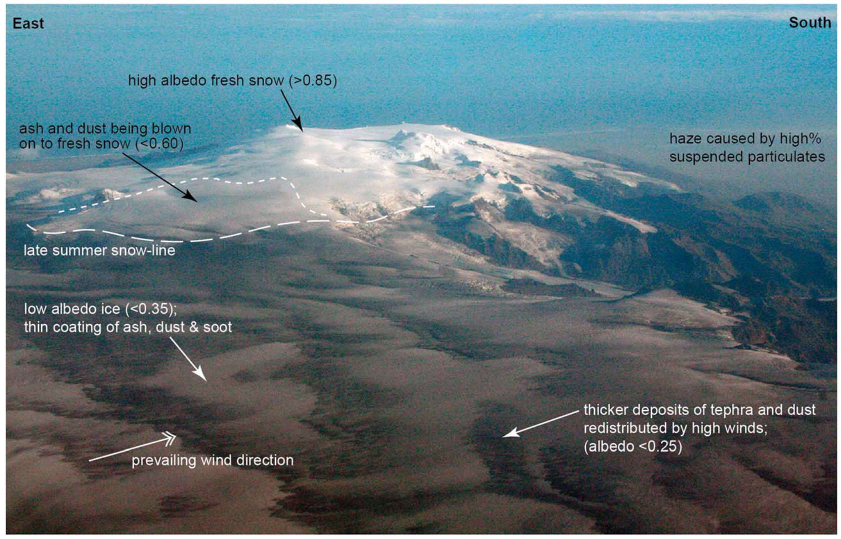

Figure 5. Oblique aerial view of the dust and ash covering on Vatnajökull, Iceland. Photo taken on 13 September 2011, three months after the Grimsvötn eruption. Note the clear demarcation between highly reflective fresh snow and much darker ash/dust-covered ice on the Öræfajökull volcano. Also, note the uneven pattern of wind-blown redistributed surface sediment and high levels of particulates in suspension—evident as visibility-reducing haze (right distance).

coastline occurs during autumn, when light is low [*Crusius et al*., 2011]. This does not imply that this dust is unimportant as an Fe source to the iron-limited subarctic North Pacific but rather that the biological response might be delayed until light levels increase.

In addition to their potential impact on marine ecosystems, dust, fine particulate matter, and other aerosols ($<100\ \mu$m) play an important role in the cryosphere, mainly through their impact on the mass balance of ice sheets and glaciers. Wind-transported fine-grained debris accumulates on snowfields and glaciers like all other natural land surfaces (Figure 5), where it darkens the snow or ice surface leading to a decrease in albedo (or reflectivity) and an increase in short-wave solar radiation absorbed by the ice [*Paterson*, 1994; *Tedesco et al*., 2008]. This physical relationship between ice surface darkness (albedo) and incoming radiation absorption strongly controls the degree of surface melting by ablation and hence the surface mass balance of glaciers.

Mineral dust, ash (tephra), and soot (black carbon) all strongly absorb radiation in visible wavelengths. When found extensively on the surface of snowfields and glaciers, they can greatly affect the albedo of the ice mass, enhancing melting and altering the surface mass balance. For example, modeling studies of the Greenland Ice Sheet (GrIS) have shown that a decrease in albedo of just 1% in fresh snow across the whole ice mass could lead to a 12% decrease in annual ice accumulation—equivalent to a surface mass loss of $-27\ \mathrm{Gt\ yr^{-1}}$ [*Dumont et al*., 2014]. Using remote sensing MODIS satellite data, *Dumont et al.* [2014] identified a decrease of 2–5% in springtime snow albedo between 2003–2008 and 2012. They attributed this to an increase in light-absorbing impurities, such as dust, soot, and cyanobacteria, falling on GrIS snow since 2008. In situ samples of dust from an unusual "dark region" on the western margin of the GrIS were collected and analyzed by *Wientjes et al.* [2011]. They used geochemical analyses and microscopy to show that the dust grains did not originate from volcanic eruptions or from low-latitude deserts but rather that the dust was locally derived from nonglacierized parts of Greenland or nearby high-latitude source areas experiencing high levels of aeolian activity. The occurrence of these darker dust-rich zones on the ice sheet surface could provide an important positive feedback through the albedo-controlled melt rate of ice [e.g., *Bøggild et al*., 2010; *Wientjes and Oerlemans*, 2010; *Dumont et al*., 2014]. Dust and organic material blown onto the ice can be dispersed or accumulated in cryoconite holes forming biological "hot spots" on the ice [*Yallop et al*., 2012; *Cook et al*., 2016]. In addition to affecting terrestrial ice, the accumulation of mineral aerosol also affects the melt rates of sea ice. The affect of dust deposition is strongly influenced by the characteristics of the snow and ice and has, for example, less impact on the albedo of cold polar snow than on melting sea ice [*Lamare et al*., 2016].

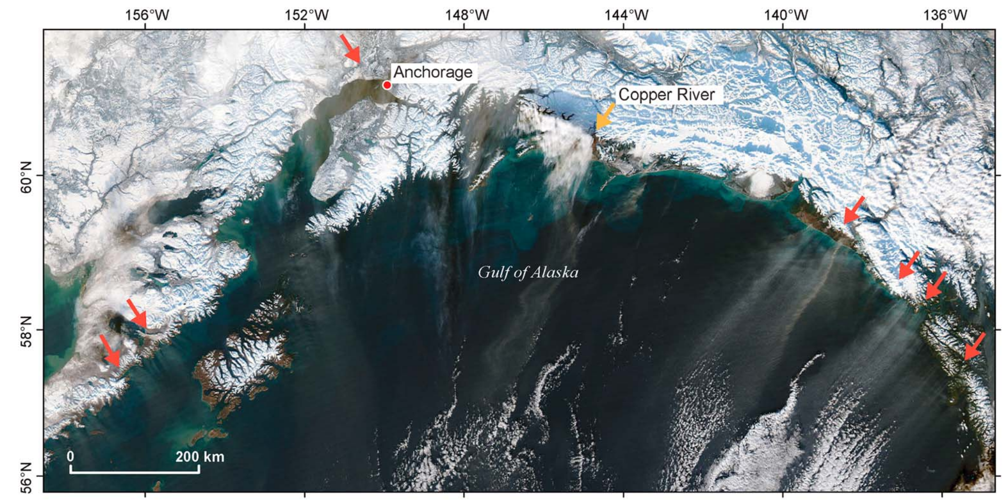

Figure 6. MODIS Terra image 26 February 2011 showing multiple dust plumes being transported over the Gulf of Alaska. Arrows indicate the dominant dust sources.

Over longer timescales, dust has been settling and accumulating on the major ice sheets throughout much of the Quaternary Period and there is strong evidence for a close coupling between dust and climate that has been sustained through multiple glacial-interglacial cycles [*Lambert et al*., 2008]. Calcium concentrations, a proxy for terrestrial dust within the GRIP ice core, show marked fluctuations in dust concentrations at Northern Hemisphere high latitudes over the last 100,000 years [*Mayewski et al*., 1997; *Fuhrer et al*., 1999; *Ruth et al*., 2003]. Dust peaks are associated with the onset of stadial conditions due to the combined effects of aridity, a weakened hydrological cycle, strong tropospheric winds, a reduction in terrestrial biomass, and extensive fine sediment availability [*Bullard*, 2013]. Low dust concentrations are associated with warmer interstadials. Mineralogical and isotopic analyses of dust in Greenland ice cores suggest a low-latitude Northern Hemisphere source [*Bory et al*., 2003b], with the central Asian desert belt being most likely. Nevertheless, dust emission related to increased exposure of potential source areas on high-latitude continental shelves during glacial periods of eustatically low sea level has not been ruled out [*De Angelis et al*., 1997; *Fuhrer et al*., 1999]. Since these discoveries, the high-resolution GrIS dust record has been used as a proxy for reconstructing wider Northern Hemisphere atmospheric paleocirculation patterns [*Mayewski et al*., 1994; *Sun et al*., 2001; *European Project for Ice Coring in Antarctica Community Members*, 2006]. Some studies have suggested an interhemispheric link between Greenland's dust record and Antarctic temperature variability over the last 80,000 years [*Barker and Knorr*, 2007].

4. Regional High-Latitude Dust Sources

4.1. Alaska

Dust storms in southern Alaska were first reported at least a century ago [*Tarr and Martin*, 1913]. Most of our understanding of contemporary Alaskan dust has been gained from analysis of dust deposits, in the form of modern loess in central Alaska, or from satellite remote sensing. However, it was only in 2011 that the first publication described widespread dust storms occurring, often simultaneously, at many different locations spanning much of the Gulf of Alaska coastline [*Crusius et al*., 2011] (Figure 6). Dust storms occur in these locations in response to a fairly predictable set of phenomena described in more detail in *Crusius et al*. [2011]. The many glaciers that cover much of this very mountainous coastline melt during the summer, driving a maximum in river discharge at that time (Figure 7). This river discharge contains considerable quantities of fine glacial flour, part of the bedrock eroded as glaciers advance over the landscape. In the autumn, after most of the melting ceases, but before significant snowfall, extensive river floodplains are exposed that are covered in recently deposited glacial flour. High-pressure systems over central Alaska, coupled with autumn cooling events, can drive strong northerly winds that can be channeled down the steep mountain valleys (katabatic winds), resuspending the fine glacial flour as dust and transporting it far over the ocean. The most prominent valley where this occurs is that of the Copper River, the single largest source of freshwater to the

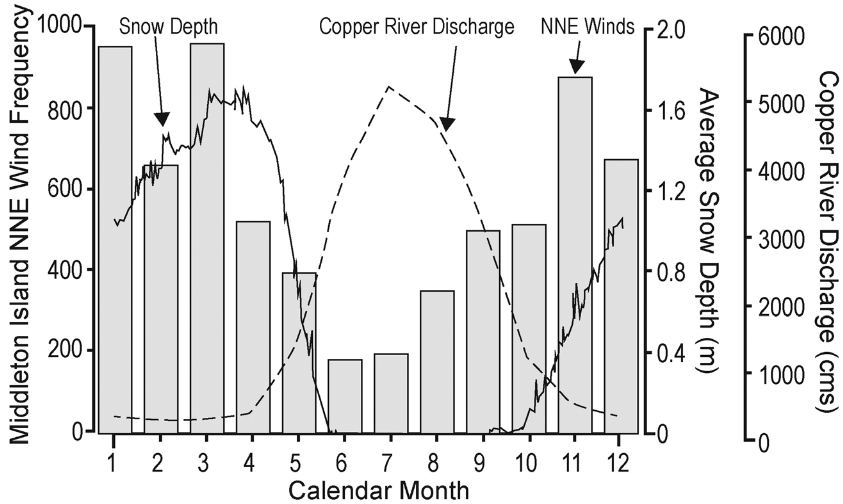

Figure 7. Monthly variation in frequency of down valley (NNE) winds, snow depth, and river discharge in the Copper River catchment, Alaska [*Crusius et al.*, 2011].

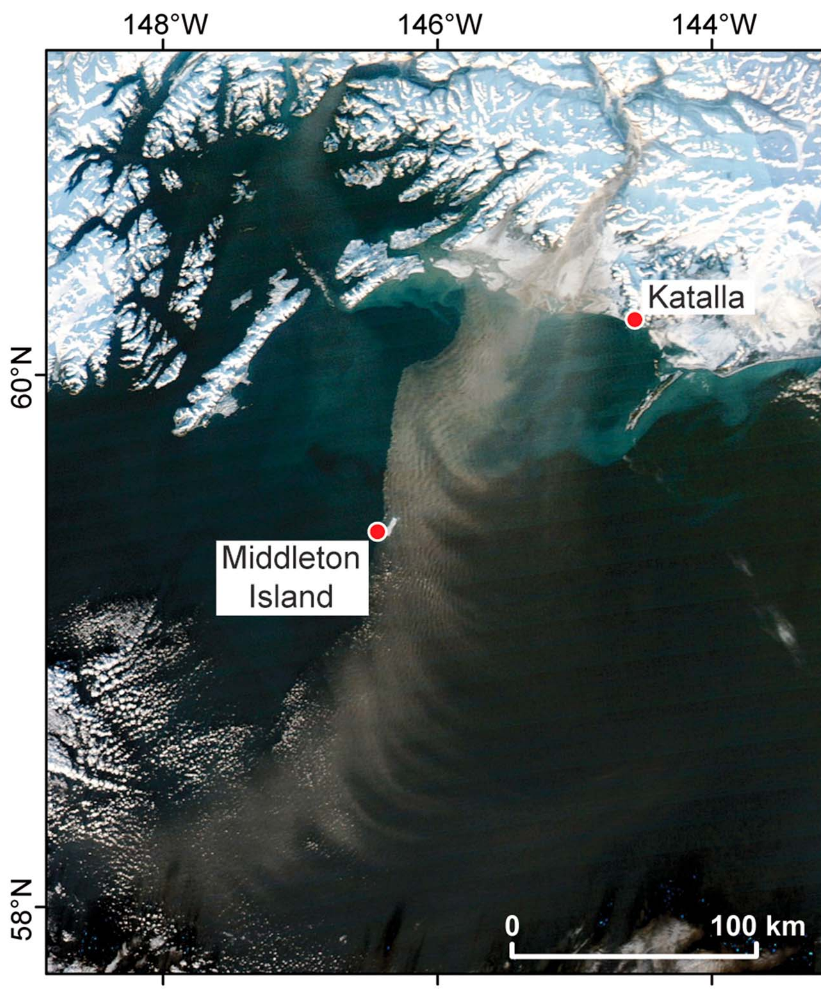

Figure 8. MODIS Aqua image 4 December 2012 showing a major dust plume originating from the Copper River valley and extending >200 km over the Gulf of Alaska.

Gulf of Alaska. However, similar phenomena have been observed to occur at many sites along the roughly 1000 km of glacierized coastline. From 2011 to 2014, dust observations were carried out on Middleton Island (J. Crusius, personal communication, 2015), near the continental shelf break in the pathway of the most prominent dust plume [see *Crusius et al.*, 2011] (Figure 8). Those observations confirm the events as summarized above, in addition to revealing strong interannual variability.

MODIS satellite images show that dust transported offshore over the Gulf of Alaska extends at least a few hundred kilometers over the ocean. Alaskan dust has been demonstrated as containing a high proportion of iron [*Schroth et al*., 2009], and *Crusius et al.* [2011] estimated that the quantity of bioavailable iron transported to this iron-limited region of the north Pacific Ocean via dust is comparable to that transported offshore in coastal eddies [e.g., *Xiu et al*., 2011]. As yet there is insufficient evidence that these autumn dust events lead directly to phytoplankton blooms, most likely because light levels are low when they occur. However, the dust nonetheless contributes significantly to the available inventory of bioavailable iron in the Gulf of Alaska, and it is possible that it could remain in solution long enough to fuel phytoplankton blooms in the spring when bloom conditions improve. Dust is also deposited on land, where observations from loess deposits demonstrate that similar dust deposition has been occurring for millennia [*Muhs et al*., 2013, 2016]. Dust storms originating from the glacial river valleys of the Knik, Matanuska, and Susita Rivers in Alaska can affect air quality in the state capital Anchorage. The U.S. Environmental Protection Agency standard for air quality is 150 μg m^3 of particles $<$10 μm diameter (PM_{10}) averaged over 24 h, and this standard was exceeded due to natural dust storms in 2001, 2003, 2007, 2009, and 2010 with 24 h average PM_{10} concentrations $>$500 μg m^{-3} during the most severe events [*Department of Environmental Conservation*, 2012].

4.2. Canada

Contemporary dust events are relatively rare in Canada compared to other high-latitude countries, with the majority of documented observations pertaining to events occurring in late winter through spring in the Prairie Provinces, particularly within a seasonally cold, dryland area referred to as Palliser's triangle in southern Saskatchewan and Alberta. In selected periglacial settings within Arctic Canada such as on glaciofluvial outwash and dry lake beds, small-scale dust emission events are also known to occur. However, many reports relating to these events are either anecdotal or buried in the grey literature (e.g., aviation and air quality records). To date, the most well-known and rigorous investigation of dust emission in a western Arctic setting within Canada was carried out by *Nickling* [1978] who directly measured the vertical flux of dust produced from outwash sediments within the Slims River valley in the Yukon Territories under strong off-glacier winds. This seminal work provides the only detailed set of measurements of dust emission carried out in a proglacial setting within Canada. Occasional, serendipitous sightings and observations of dust plumes have been made by other researchers working in remote locations while studying other phenomena. For example, *Church* [1972] made some "indicative" measurements of dust storms on the Lewis River sandur in July 1965 during his study of Arctic fluvial processes. He noted that "considerable quantities of dust were found at 100 cm above the ground" (p. 64) and recorded dust covered snowpacks in the spring. The remote sensing record of dust in Canada is very limited, although occasional events have been detected.

Lacustrine, glaciofluvial, and aeolian (loess) deposits are extensive and well documented in maps of the surficial geology of Canada [*Fulton*, 1989], and it would be expected that dust may be emitted from these surface types and transported tens of kilometers up to as much as 500 km from their local source. Relatively warm, dry (Chinook) föhn winds that descend from the Rocky Mountains in late winter and early spring are strongly associated with dust emission from unprotected, tilled soils in western Canada. Cold, dense katabatic winds draining from upland ice caps also play a role in proglacial systems throughout northern Canada, particularly in the high and eastern Arctic. Topographic funneling through deep glacial valleys within fjord settings leads to substantial acceleration of such winds, which may exceed 28 m s^{-1} (100 km hr^{-1}) in extreme situations. In terms of seasonality, dust emission from undisturbed sources is relatively uncommon in summer, except under conditions of severe drought, as the surfaces are usually either well protected by a vegetation cover (e.g., moss, lichen, and macrophytic plants) or submerged in the case of the nival melt affecting outwash plains. However, aeolian transport is reported to increase again through the fall months as water levels drop, the vegetation cover becomes dormant or dies off with heavy frosts, and wind speeds increase with large-scale meteorological shifts associated with the change of season and the positions of the jet stream and

Figure 9. Dust event at Kangerlussuaq, SW Greenland, 1 July 2014. Photograph courtesy of Tom Matthews.

the Icelandic and Aleutian low-pressure systems. In the Canadian Arctic, aeolian transport is believed to peak at this time of year but may continue into winter in isolated areas where a snowpack is not well developed or absent altogether. Where the snowpack is present and is relatively dry and granular, blowing snow may expose large areas of bare unprotected surface to subsequent sublimation and entrainment, as well as abrasion under particle impact [*Edlund and Woo*, 1992]. Extensive niveo-aeolian deposits observed in winter throughout Canada provide some of the best evidence we have of the coincident transport of mineral and snow particles within a given boundary layer flow [e.g., *Lamoureux and Gilbert*, 2004].

The surface characteristics and conditions described above suggest that dust storms should be frequently observed in Canada, but this is not the case (Figure 3). A very low population density, limited number of observing meteorological stations, and problems with the use of remote sensing data (section 5) may partially explain this. Another contributing factor is improvements in soil conservation practices which have reduced, if not completely eliminated, the occurrence of wind erosion events on tilled soils. The presence of vegetation, a snowpack, and cementing or crusting (e.g., by pore ice, salt, clay, or organic material) do suppress a lot of dust emission, but anthropogenic activities associated with agriculture, transport, construction, and mining can disrupt these suppressants and lead to localized dust storms.

Most dust is deposited locally ($<$30 km) on glacier surfaces, higher elevation valley slopes, upland permanent snowpacks, and on ice-covered lakes, rivers, and fjords (ultimately ending up in lacustrine and marine sediments). Long-range transport from sources in the Canadian Arctic has not been documented. Where there is significant accumulation of wind-blown silt, the albedo of the surface is altered affecting the energy balance and melt rate of either the snow or ice pack. For example, an experiment by *Edlund and Woo* [1992] on Ellesmere Island showed that snowmelt could be accelerated by a week by a dust layer with a concentration of 1230 g m^{-2}. The finest particles (e.g., $PM_{2.5}$) sampled from snow and ice packs in the Canadian Arctic are associated with long-range transport on a global scale, much of it believed to arrive from Asia in late winter through spring. In comparison, mineral dust particles deposited during the autumn season generally contain coarser particles, so that local sources are believed to play a more significant role at this time of year [*Zdanowicz et al*., 2000].

4.3. Greenland

Early expeditions to Greenland reported strong winds and dust storms in ice-free areas prompting *Hobbs* [1931, 1942] to conclude that wind was likely to be more important than meltwater for the transportation of sediment in proglacial regions. One of the earliest comparisons of the geomorphological effectiveness of the wind between the Arctic and Tropical latitudes was also based on work in west Greenland. In this, *Fristrup* [1953] suggested that geomorphologically active dust storms are likely to be more frequent and longer lasting in the Arctic than in the Tropics with the effects enhanced by the abrasion of snow and ice. More recently, *Dijkmans and Tornqvist* [1991] described dust clouds on ice and vegetation-free sandur plains near Kangerlussuaq, SW Greenland, reaching over 100 m high during winds of 14–18 m s^{-1} which are not uncommon (Figure 9). To date, all records of dust storms in Greenland have been based on field observations from expeditions or dedicated field campaigns [e.g., *Bullard and Austin*, 2011]. Greenland dust storms remain undetected by remote sensing although deposition of locally derived dust on to the ice sheet has been observed [*Wientjes et al*., 2011].

Potential dust sources in Greenland are confined to ice-free areas of the land mass. Although this accounts for ~19% (~400,000 km^2) of the land mass, only a small fraction, primarily vegetation-free active glacial

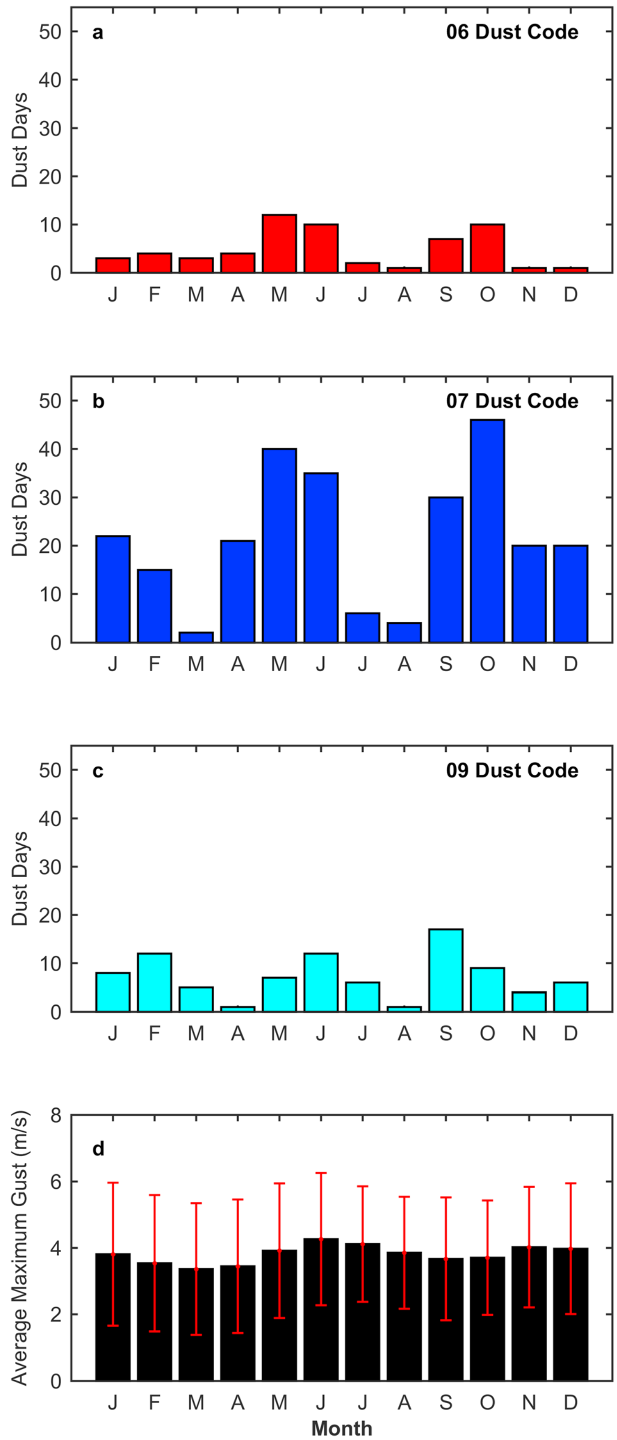

Figure 10. Seasonal variability of dust days at Kangerlussuaq, Greenland, (1942–2015) for (a) widespread dust in suspension, not raised by wind at or near the station at the time of observation (dust code 06); (b) dust or sand raised by wind at or near the station at the time of observation (dust code 07); (c) dust or sandstorm within sight at time of observation or at the station during the preceding hour (dust code 09); and (d) Mean and standard deviation of maximum wind gusts recorded at Kangerlussuaq (1942–2015).

outwash plains, is actually dust sources. *Bullard and Austin* [2011] found predominantly bimodal sands and gravels at the surface of the outwash plains with lag deposits that limit aeolian entrainment but identified a clear link between meltwater floods that deposit thick layers of fine sediment (<100 μm diameter) across the floodplain and seasonal dust storms. Figure 10 shows the seasonal variability of days when dust was recorded at Kangerlussuaq meteorological station (1942–2015) based on dust codes [*O'Loingsigh et al.*, 2010]. For dust code 06 (widespread dust in suspension, away from station) and dust code 07 (dust or sand raised by wind at or near the station at time of observation) there is a peak in dust days in both spring and autumn. Events coded 09 (dust or sand storm within sight at time of observation or preceding hour) occur most frequently in the autumn. Sediment supply to the floodplains is closely coupled to the delivery of material during spring and fall flood events; however, the record of dust days suggests that all three types of dust event can occur year round. *Hobbs* [1931] suggested that strong winds may cause a high frequency of dust storms in winter in Greenland; however, the monthly variability in average maximum wind gusts suggests no strong seasonal variation for the Kangerlussuaq area (Figure 10).

In addition to the floodplains, loess deposits 0.5–1 m thick and covering $70 \times 10^6\,km^2$ around the western margin of the Greenland Ice Sheet actively accumulate aeolian sediments. Despite a vegetation cover >70% in some areas, these aeolian deposits are characterized by deflation hollows caused by local wind erosion [*Dijkmans and Tornqvist*, 1991]. These deflation hollows are more common closest to the ice sheet and thought to be caused primarily by katabatic winds [*Heindel et al.*, 2015]. Ongoing wind erosion of fine soils (~40 μm) in the hollows may also contribute to local atmospheric dust.

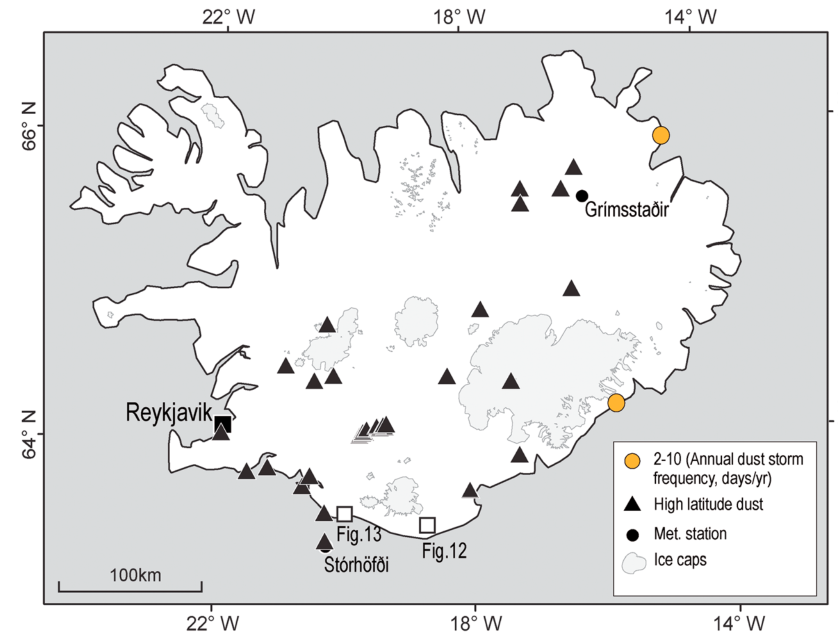

Figure 11. Observations of high-latitude dust in Iceland where filled circles indicate dust storm frequency based on visibility data and black triangles indicate georeferenced published observations of dust storms (see text for details).

The majority of dust generated in Greenland is likely to be deposited locally or regionally. The modern loess deposits near Kangerlussuaq (Søndre Strømfjord) extend about 80 km west of the ice margin. Some locally derived dust is thought to be transported iceward and may be deposited on the ice causing surface darkening as it changes the ice albedo [*Wientjes et al*., 2011]. Recently, there has been increased recognition of the possible impacts of dust inputs on the ecology of lakes in Arctic and alpine regions [*Mladenov et al*., 2011, 2012]. *Anderson et al.* [2016] suggest that aeolian deposition adds 50 mg of carbon m^{-2} yr^{-1} to soils and lakes near Kangerlussuaq. In southwest Greenland there are ~20,000 lakes but the effects of dust input to lacustrine sediments and processes in this region have not been explored in detail.

4.4. Iceland

The best studied high-latitude dust area is Iceland. More than 15 research papers have been written focusing on the sources and impacts of wind erosion in the country (Figure 11). This is due to the prevalence of aeolian activity driven by climate, volcanic activity and glacial sediment supply, and also the impact of humans. Iceland was settled around AD 874, and land-use practices and the introduction of grazing animals has caused severe vegetation depletion and soil erosion [*Dugmore et al*., 2009; *Gísladóttir et al*., 2011]. Evidence of widespread and sustained wind erosion can be found in historical records, such as sagas, annals, old farm surveys and place names, as well as from expeditions [*Arnalds et al*., 2001a].

Sandy deserts with active aeolian processes cover $>$20,000 km^2 (~20%) of Iceland and their distribution is closely associated with the island's ice caps, as well as with volcanic systems and eroded soils [*Arnalds et al*., 2001b; *Arnalds*, 2010]. Unlike many other high-latitude dust source areas, Iceland has a good and relatively dense network of weather stations. Meteorological records (1949–2011) suggest that an average of 34 dust days per year occur in Iceland, but that the frequency increases substantially when dust haze and events caused by the resuspension of volcanic materials are taken into account [*Dagsson-Waldhauserova et al*., 2014]. The most active source regions for dust storms are the sandur areas on the southern coast (Figure 12) and the area northeast of the largest ice cap Vatnajökull. The seasonal temporal pattern is driven primarily by sediment supply and winds in southern Iceland and snow cover in the north. Glacial meltwater on the southern coast is distributed across broad glacial outwash plains where peak discharge is typically in spring and highest suspended sediment loads are in April with a second weaker peak in September [*Gíslason et al*., 1997; *Old et al*., 2005]. This fine suspended sediment load is deposited as extensive silt drapes across the sandur from which it can easily be entrained by strong winds. Meltwater sediment supply can dramatically

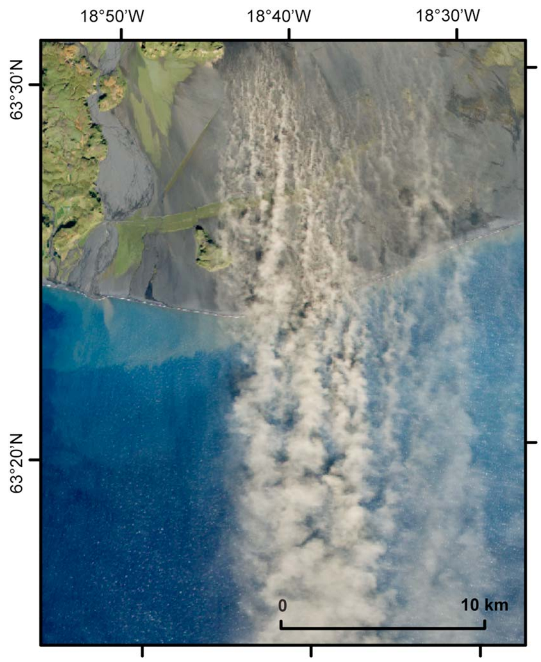

Figure 12. Landsat image 17 September 2013 of Mýrdalssandur, Iceland, showing multiple small dust plumes blowing south over the Atlantic Ocean.

increase during catastrophic flood events (jökulhlaups) triggered by volcanic or glacial activity, which have been linked to increases in dust storm activity [*Prospero et al*., 2012]. Dust storms generally occur when weather is, or has been, dry and wind speed ranges from 5 to 10 m s^{-1} depending on surface roughness (Figure 13) [*Arnalds et al*., 2001b; *Gísladóttir et al*., 2005]. Extraglacial snow cover is low in southern Iceland and not thought to be a major control on dust emissions. By comparison, snow cover is higher and lasts longer in the northeast of the country, increasing the required threshold wind velocity for dust entrainment and reducing the frequency of dust storms [*Dagsson-Waldhauserova et al*., 2013]. The differences in the seasonal distribution of dust days in the south and northeast of Iceland are clearly seen in Figure 14. Although dust storms occur all year round in southern Iceland, dust storm frequency is highest during the spring, with a second, lower peak in the fall. In northeast Iceland, dust storms are prevalent in the summer months.

Icelandic dust storms are not only linked to the glacial system but can also be caused by the resuspension of widespread volcanic ash deposits associated with the active volcanic zone. The eruption at Eyjafjallajökull, 14 April to 20 May 2010, produced abundant particulate matter due to its explosive eruption style. Even after the volcanic activity ceased, high particulate matter (PM) concentrations were still measured on several occasions, due to resuspended ash (Figure 2). After the eruption ceased, values as high as 8000 μg m^{-3} (10 min average), and 900 μg m^{-3} (24 h average), were measured because of resuspension of freshly deposited fine ash. In Reykjavík, 125 km WNW of the volcano, the PM_{10} concentration reached over 2000 μg m^{-3} (10 min) during a resuspended ash storm on 4 June 2010 [*Thorsteinsson et al*., 2012].

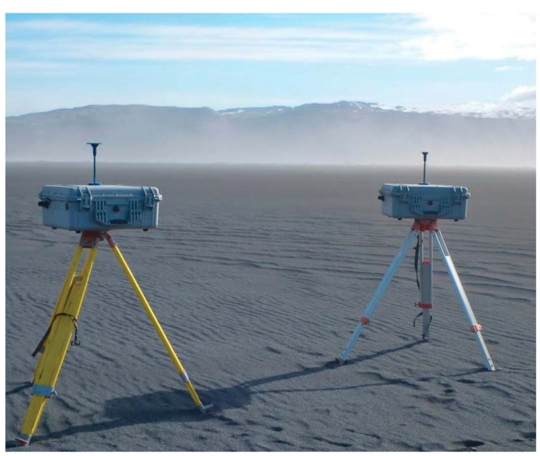

Figure 13. DustTrak monitors being used to measure the concentration of atmospheric dust during a storm near Landeyjarsandur, June 2015.

The impacts of dust storms in Iceland can be identified both at the dust source and off-site. Local redistribution of soils and sediment results in coarser soil textures [*Ólafsdóttir and Guðmundsson*, 2002; *Jackson et al*., 2005; *Dugmore et al*., 2009; *Gísladóttir et al*., 2010] as soils lose their fine material and light particles such as soil organic carbon. Some material is transported offshore [*Óskarsson et al*., 2004; *Gísladóttir et al*., 2010], and some is deposited locally in soils or into sediment traps such as lakes [*Gathorn-Hardy et al*., 2009; *Geirsdóttir et al*., 2009]. Dust deposition rates in Iceland range from 13–26 g m^{-2} yr^{-1} in the northwest to >250 g m^{-2} yr^{-1}

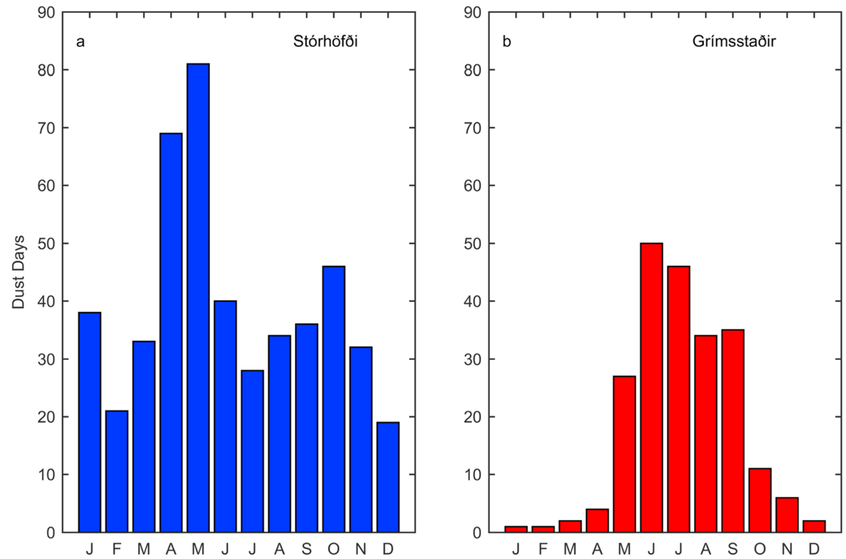

Figure 14. Seasonal variability of dust days (dust code 06) in (a) Stórhöđi, southern Iceland, and (b) Grímsstađir, northeast Iceland, for 1992–2012.

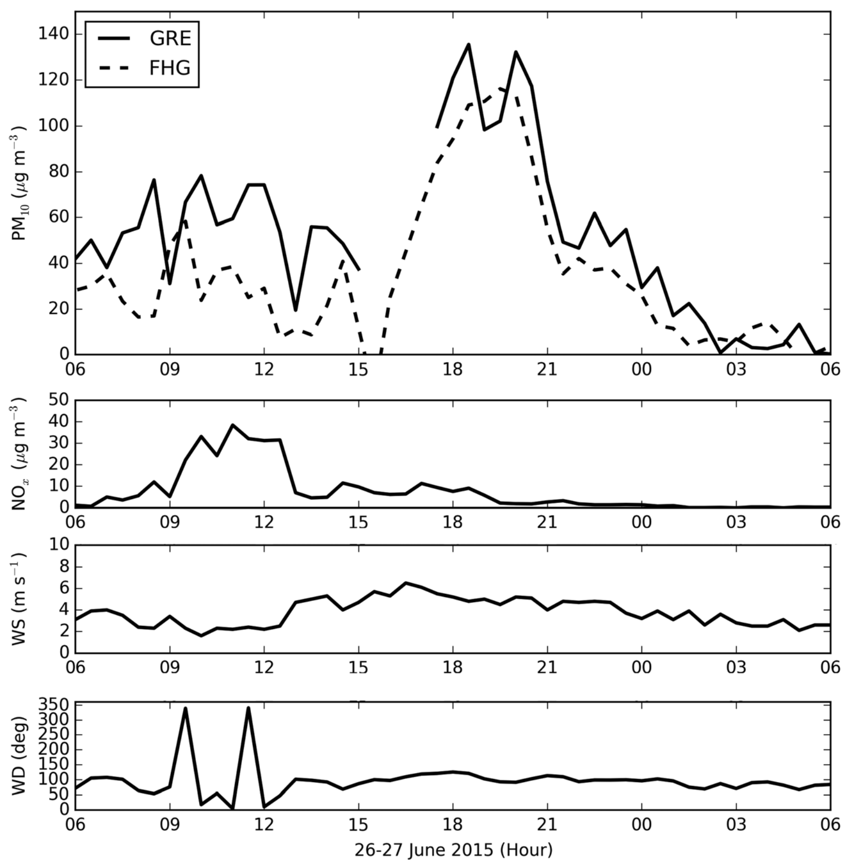

Figure 15. Concentration of PM_{10} measured in Reykjavík on 26–27 June 2015. Morning PM_{10} measurements can be attributed to NO_2 whereas an increase in wind speed (WS), and stabilization of wind direction (WD) in the afternoon increased PM_{10} which is attributed to a dust storm.

along the south coast, through the central volcanic belt and in the northeast [*Arnalds*, 2010]. Dust can be transported over the ocean to the northeast, but most is transported south where it may contribute bioavailable iron to the Atlantic [*Arnalds et al.*, 2014] or west-north-west toward the capital Reykjavík. Dust storms account for around one third of the air quality exceedance events (PM_{10} concentration $>50\ \mu g\ m^{-3}$) in Reykjavík each year [*Thorsteinsson et al.*, 2011] (Figure 15). They can occur at any time of year and may occur in combination with snow storms during the winter [*Dagsson-Waldhauserova et al.*, 2015; *Liu et al.*, 2014].

4.5. Antarctica

Antarctica is predominantly ice covered with only 2% comprising ice-free land. Most of the focus on dust in Antarctica has centered around ice core records, which clearly indicate that the continent receives dust from two key global dust sources. One of these sources is Australia which is the largest contributor of dust under the current climate [*Li et al.*, 2008]. The second major dust source affecting Antarctica is another high-latitude region, southern South America. Dust from this source, which includes Patagonia and Tierra del Fuego, dominates records in the Antarctic Peninsula and West Antarctica and accounts for up to 85% of dust in the Lake Vostok core [*Li et al.*, 2008]. Although southern South America is not currently the dominant source, it is thought to have been more important than Australia during the Last Glacial Maximum [*Albani et al.*, 2012]. Southern South American dust sources are discussed in section 4.7. Analysis of dust in coastal ice cores, e.g., Taylor Dome, suggests that present-day Holocene dust originates from the ice-free areas of Antarctica [*Delmonte et al.*, 2013].

The ice-free areas of Antarctica have recently been recognized as important local dust sources. Of these, the McMurdo Dry Valleys are the largest ice-free area (4800 km^2) [*Doran et al.*, 2002] and the most notable dust source. The remoteness and harsh conditions of Antarctica mean that there have been few field studies of aeolian processes, and many of these have focused on dunes and granular ripples rather than dust storms [*Lindsay*, 1973; *Selby et al.*, 1974; *Speirs et al.*, 2008; *Gillies et al.*, 2012]. Proglacial sandur and deflation lag surfaces characterize the lower parts of the dry valleys with aeolian sand dunes restricted to relatively confined areas. Some parts of the dry valleys may also have been occupied by proglacial lakes [*Hendy et al.*, 2000], and moraines formed by previous ice advances are also present and contain fine sediments. *Selby et al.* [1974] noted that although the aeolian deposits of the Dry Valleys comprise coarse sands and gravels, finer sediments are present in the glacial outwash and could be blown iceward onto the nearby glaciers. *Lancaster* [2002] found that silt and clay deposition dominated on nearby glaciers and ice-covered lakes (up to 95% of aeolian sediment flux) compared with the valley floors which had more aeolian sand deposition and received higher total aeolian fluxes.

Winds in the Dry Valleys are primarily topographically driven katabatic and föhn winds. Easterly onshore (up valley) winds are very persistent, but less frequent down valley winds are stronger [*Clow et al.*, 1988; *Doran et al.*, 2002]. The magnitude of the difference is seasonally variable as the strength of the up-valley winds weakens during the winter [*Lindsay*, 1973]. Short duration field studies (a few years) have found aeolian activity in the Dry Valleys to be annually very variable making it difficult to draw reliable conclusions about typical annual rates of dust transport or deposition [*Lancaster*, 2002; *Malin*, 1992; *Gillies et al.*, 2013]. Snowpits offer a greater timespan of contemporary dust deposition and using a 35 year chronology (1965–2000) *Ayling and McGowan* [2006] suggested that aeolian transport is greatest in the winter when westerly föhn winds dominate. *Atkins and Dunbar* [2009] and *Chewings et al.* [2014] measured deposition of aeolian sediments on sea ice in McMurdo Sound (Figure 4) and found that substantial quantities of material are transported offshore each year (0.2–55 $g\ m^{-2} yr^{-1}$). These sediments are deposited as a plume containing increasingly fine particles with distance downwind. Sand-sized aeolian sediments are typically transported <5 km offshore, but silts and clays were found >100 km from source and when the sea ice melts these contribute to both ocean floor sedimentation and marine nutrients. The source of these aeolian plumes is the McMurdo Ice Shelf supraglacial debris bands rather than the McMurdo Dry Valleys. *Chewings et al.* [2014] suggest that the lack of input from the Dry Valleys is due to the well-developed deflation lag that protects the surface sediments in the valleys and topographic barriers between the Valleys and the ice shelf.

Although total local dust emission from Antarctica may currently be low compared with some other high-latitude dust sources, it is predicted to increase in future as the sediments have the potential to produce dust under slightly warmer and windier conditions [*Bhattachan et al.*, 2015; *Hedding et al.*, 2015]. In addition, any

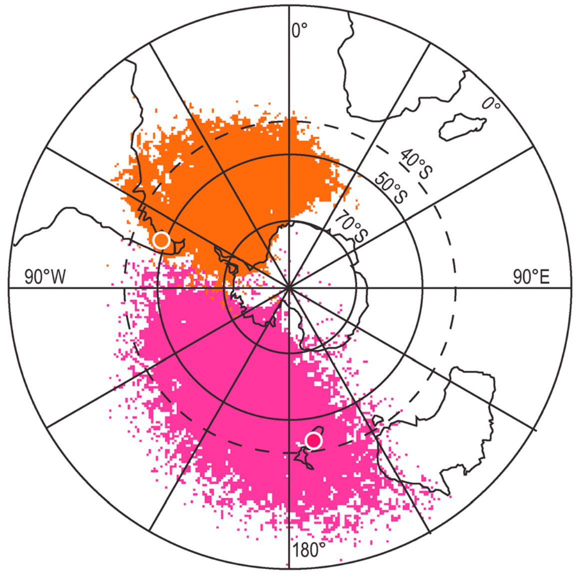

Figure 16. Five day HYSPLIT forward trajectory end points, initiated every day from 1979 to 2013 for potential source areas (circles) in New Zealand (magenta) and Patagonia (orange). The majority of end points stay within the high latitudes (south of 40°S). The 50°S indicates the Southern Ocean and 70°S Antarctica (see Figure 17). Redrawn from *Neff and Bertler* [2015].

shift from marine-terminating to land-terminating glaciers will increase the area of sediment-rich proglacial floodplains [*Bullard*, 2013].

4.6. New Zealand

Studies of contemporary dust processes in New Zealand are relatively few but have nevertheless provided a good overall understanding of both the primary sources of deflated sediment and the mechanisms driving its emission. On the country's South Island, the floodplains of extensive braided river systems are well established as a supply of fine sediment that is prone to deflation [*McGowan*, 1997; *Eden and Hammond*, 2003]. Exposed bars and inactive channels in these alluvial systems commonly act as emissive surfaces, and several field studies have quantified rates of dust deposition downwind of braided floodplains [e.g., *Cox et al*., 1973 cited by *Marx and McGowan*, 2005; *McGowan et al*., 1996; *Eger et al*., 2012]. In the semiarid rain shadow region east of the Southern Alps, degraded tussock grasslands are also recognized as a prominent source area for dust, with land erodibility within the intermontane basins of such high-country rangelands (e.g., Mackenzie Basin) having been exacerbated by anthropogenic activity [*McGowan and Ledgard*, 2005]. Vegetation removal associated with agriculture following the arrival of European pastoral practices and rabbit infestations led to peak levels of land degradation occurring in the 1940–1950s [*McGowan and Ledgard*, 2005]. In the rangelands, wind erosion has left remnant pedestals, perhaps partly related to surface-disrupting frost action [*Basher and Webb*, 1997; *McGowan and Ledgard*, 2005].

While the rain shadow effect of the Southern Alps range promotes dust emission in drier conditions on its leeside, the uplift of dust from alluvial floodplains and its subsequent local deposition have also been reported in superhumid areas on the South Island west coast, where the process is linked to active loess formation [*Eden and Hammond*, 2003; *Marx and McGowan*, 2005; *Eger et al*., 2012]. Approximately 19% of the South Island has been assessed as affected by wind erosion to some degree [*Salter*, 1984]. For instance, wind erosion of cultivated arable lands on the Canterbury Plain is well recognized, and rates of bulk soil loss have been estimated; however, specific fluxes of dust-sized material in suspension are not well quantified for these agricultural systems [*Basher and Painter*, 1997].

An important consideration in understanding New Zealand's dust sources is its location within a major transport pathway of desert dust originating from Australia [e.g., *McGowan et al*., 2001; *Eden and Hammond*, 2003]. For suspended sediment collected in New Zealand, approaches that can determine the provenance of the dust have proved especially useful in determining the component of dust from local versus long distance sources [*Marx et al*., 2014]. The geochemical modeling of collected aerosol, referenced to a database of trace elements, has been used to estimate the proportion of sampled dust coming from New Zealand or remote Australian sources. Using this approach, dust deposition episodes in which high proportions of New Zealand material were detected have been tied to braided river systems as probable sources [*Lavin et al*., 2012; *Marx et al*., 2014].

Episodes of blowing dust from New Zealand source surfaces are commonly associated with particular meteorological conditions and are typically the product of infrequent high-magnitude storms. In the austral winter, entrainment of dust on the South Island is typically associated with a strong anticyclonic presence in

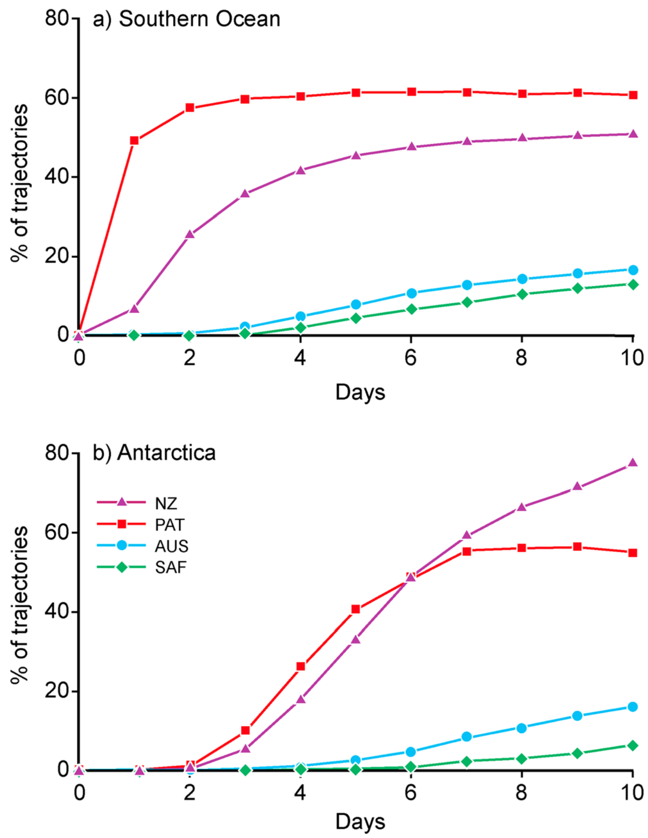

Figure 17. The percentage of 1979–2013 daily forward trajectories (12,775 in total) passing over (a) the Southern Ocean (trajectories ending south of 50°S) and (b) Antarctica (trajectories ending south of 70°S) for New Zealand (NZ), Patagonia (PAT), Australia (AUS), and southern Africa (SAF). Redrawn from *Neff and Bertler* [2015].

the northern Tasman Sea and the generation of strong south westerly winds [*Marx and McGowan*, 2005; *Marx et al.*, 2014]. In spring and autumn, westerlies of a circumpolar nature are strongest over southern New Zealand and are capable of producing localized dust storms [*McGowan et al.*, 1996]. Topographically enhanced gradient winds also play a significant role in generating dust activity in New Zealand [*McGowan et al.*, 1996]. To the lee of the Southern Alps divide, föhn nor'westers occur in intermontane basin areas, with these winds having significant dust-lifting potential due to their combined low humidity and warm, strongly gusting flows that often exceed 30 m s^{-1} [*McGowan et al.*, 1996]. With respect to the downwind pathways for dust entrained in New Zealand, very little research has been undertaken. The first paper to focus on this was published in 2015 by Neff and Bertler who used forward trajectory modeling to examine Southern Hemisphere dust trajectories from Australia, New Zealand, Patagonia, and southern Africa (Figure 16). They found that unquantified dust emissions from New Zealand would be transported southward with an efficiency comparable to that from Patagonia and that these high latitude sources were far more likely to impact the Southern Ocean and Antarctica than lower latitude dust sources in Australia and southern Africa (Figure 17). *Neff and Bertler* [2015] also suggested that even low dust emissions from New Zealand (~10 Tg yr^{-1}) could contribute as much as 8.5% total deposition of dust over the Southern Ocean and 13.7% over Antarctica.

4.7. Patagonia, Southern South America

Patagonia, including Tierra del Fuego, is a large territory of more than 900,000 km^2, located between 39° and 55°S in southern South America. The topography is dominated to the west and south by the Andean cordillera and by dissected plateaux and low plains to the east. The regional climate of the area is strongly affected by the southern westerly winds (SWWs) which, coupled with the Andean cordillera, produce a strong, east-west gradient with annual precipitation of ~4000–7000 mm in the west to ~200 mm yr^{-1} in the east concentrated in the austral autumn and winter seasons [*Garreaud*, 2007]. To the east of the Andes, scrub-grassland vegetation closely reflects the semiarid conditions. The sparse vegetation cover and strong surface winds provide appropriate conditions for dust emissions. In general, dust activity is highest during the drier summer months, but winter and autumn dust events have also been reported [*Gaiero et al.*, 2003].

The Patagonian region has been identified as a dominant source of dust in the Southern Hemisphere during glacial periods [*Basile et al.*, 1997; *Delmonte et al.*, 2008]. Successive maritime ice sheets, fed by the SWWs and high precipitation have, in response to climate forcing, waxed and waned along the southern Andes. Each glaciation has left a legacy of glacial landforms, ice-scoured troughs, and extensive sandur plains extending across the Patagonian steppe [*Clapperton*, 1993]. During the LGM mineral dust concentrations 20–50 times higher than the present have been identified in Antarctic ice cores and radiogenic isotopic signatures of

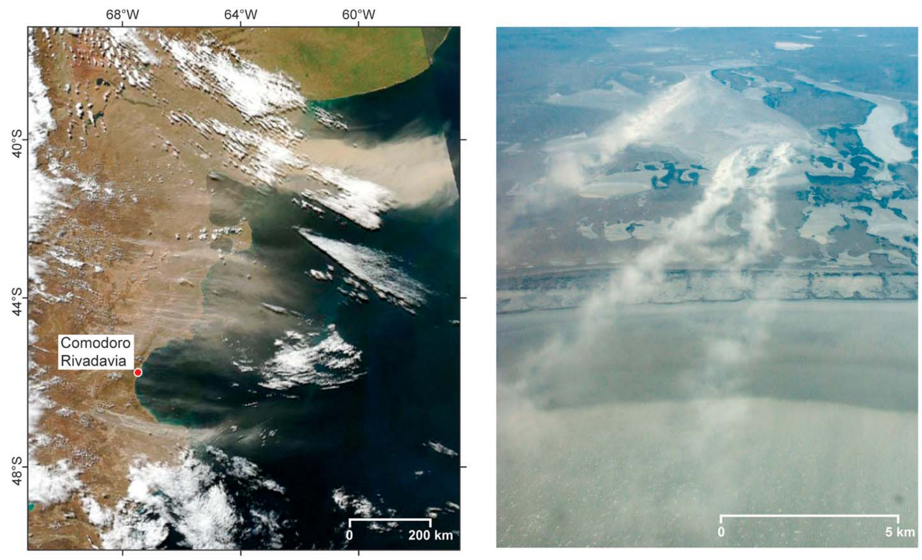

Figure 18. (left) MODIS Aqua image 28 March 2009 showing multiple dust plumes in Patagonia caused by strong westerly winds extending over the south Atlantic. The most dense plume originates from the Colorado and Negro River mouths in the north which were particularly active in 2009 due to combined drought and poor rangeland management. (right) Aerial photograph of dust storm in October 2004 caused by winds gusting to 29 m s^{-1} at San Sebastián Bay, Tierra del Fuego, 800 km south of Comodoro Rivadavia.

the dust indicate Patagonian sources [*Lambert et al*., 2008]. Atmospheric transport models coupled to global circulation models have been unable to explain the pattern of dust peaks in the ice cores [*Mahowald et al*., 1999]. As a possible explanation, the Antarctic dust signal may have been mediated by glacial geomorphological mechanisms leading to a "switching off" of dust emissions as the Patagonian ice sheets waned at the termination of the last glaciation [*Sugden et al*., 2009].

In contrast to the high dust flux of the glacial period the volumes of Holocene Patagonian dust emissions are smaller but probably continue to be a significant input into the HNLC southern ocean ecosystems and the Antarctic ice sheets (Figure 16) [*Erickson et al*., 2003; *Wolff et al*., 2006; *Gassó and Stein*, 2007]. The present Patagonian dust sources are from reworked loess, alluvial fans, large dessicated lake beds (Figure 18), and particles produced from explosive volcanism. Emissions and persistent major dust sources have been attributed to sustained meteorological and climatological conditions [*Gaiero et al*., 2013]. It is also likely that sustained over grazing of the scrub grassland since European settlement of the region has increased dust emissions [*McConnell et al*., 2007; *Gaitan et al*., 2009].

High-latitude Patagonian sources south of ~39°S are less well understood than those farther north on the continent due to the region being cloudier and the dust events being more sporadic [*Gassó et al*., 2010]. This has made it difficult to identify dust source areas and to track dust events except by proxy through the analysis of dust deposition in Antarctica [*Bory et al*., 2010]. The monitoring of air quality and sky turbidity at meteorological stations along the Argentine south Atlantic coast provides the longest records of surface dust measurements [*Mahowald et al*., 2006; *Gassó et al*., 2010]. There is a strong relationship between the austral summer drying and increased intensity of the SWWs, probably exacerbated by strong katabatic winds across the Patagonian steppe, leading to increased dust activity. Estimates that ~30×10^6 t yr^{-1} of Patagonian dust are supplied to the South Atlantic shelf [*Gaiero et al*., 2003] are considered by *Simonella et al.* [2015] to be too low.

Recent improvements in the detection capabilities of satellites have significantly advanced our understanding of the nature and extent of point sources of dust from Fuego-Patagonia and the distance the dust may travel—as much as ~1800 km from source [*Gassó and Stein*, 2007; *Gassó et al*., 2010]. Combined observation-modeling studies have improved our understanding of the transport pathways, seasonality, and efficiency of the different potential dust sources [*Genthon*, 1992; *Li et al*., 2008, 2010a, 2010b; *Mahowald et al*., 1999, 2006; *Albani et al*., 2012]. Satellite data have also verified Eulerian model outputs of aerosol distribution and identified dust sources from topographic depressions [*Li et al*., 2008; *Johnson et al*., 2010]. However, as with other high-latitude dust sources, satellite observations and modeling of Patagonian dust activity face a number of challenges (section 5.2).

4.8. Other High-Latitude Dust Sources

In addition to the seven main regional high-latitude dust sources considered above, there are other less well studied or smaller dust sources primarily in the Northern Hemisphere ≥50°N. *Dörnbrack et al.* [2010] describe a dust storm on the Norwegian archipelago of Svalbard (78°N) that occurred in May 2004. The dust sources comprised both natural sediments deflated from dry riverbeds and anthropogenic sources at active coal mines. Dust storms are not frequent on the islands but primarily occur during the autumn when river levels are low exposing dry, snow-free sediments; the May event followed dry, sunny conditions throughout April and May. The geochemistry of aerosols in Svalbard suggests not only local dust sources but also that dust is transported to the islands from Greenland and Iceland [*Moroni et al*., 2015].

Numerous locations of potential dust sources exist in central Asia and Siberia [*Engelstaedter et al*., 2003]. This mostly arid continental polar, or humid, cool climate is characterized by tundra or boreal forest. Nevertheless, locally sourced dust storms have been reported especially in those areas affected by desertification and land degradation. The frequency of dust storms in southern Siberia varies both spatially and temporally. For example, in 1988 there were 2 dust storms recorded in the Nazarovskaya area (forest steppe) but 17 on the Koibalskaya steppe (~200 km south). High annual frequencies of storms are associated with droughts (e.g., early 1920s, 1950s, 1970s, and early 1980s) and exacerbated by agricultural activities. *Bazhenova and Tyumentseva* [2015] suggested that the average rate of deflation in subarid southern Siberia is 0.1–2.5 mm yr^{-1} with the wind-blown material dominated by silts and clays. The rate of deflation and accumulation of sediments, however, are strongly linked to local topography and vegetation cover. Farther east, dust storms caused by the resuspension of volcanic ash have been observed on the Kamchatka peninsula [*Gimsey et al*., 1998].

5. Challenges in Understanding and Quantifying High-Latitude Dust

5.1. Characterizing High-Latitude Dust Sources

Table 2 summarizes the key characteristics of the main regional high-latitude dust sources examined here. It highlights the patchiness of our current understanding of dust emissions in these areas and also some common elements. Similar to subtropical dust sources, high-latitude dust sources contain fine-grained, wind erodible sediment in lows such as riverbeds, valley floors, and glacial outwash plains. Other common sources in high latitudes are reworked loess deposits which are less significant in the subtropics due to the global spatial distribution of loess [*Pécsi*, 1990; *Muhs*, 2013].

There appears to be no typical annual rainfall associated with high-latitude dust sources. Some, such as the Dry Valleys of Antarctica, receive very little precipitation; *Keys* [1980] suggested 100 mm rainfall equivalent per year, but a more recent study by *Fountain et al.* [2009] measured spatially very variable precipitation of 3–50 mm rainfall equivalent per year (1995–2006). Other high-latitude dust regions such as New Zealand (~600 mm yr^{-1}) and southern Iceland (1500–2500 mm yr^{-1}) receive high quantities of precipitation. Rather than total precipitation, it is more likely that the balance between precipitation and evaporation, combined with the distribution of snow cover and wind speed, are more important characteristics of high-latitude dust sources.

The overall relationship among sediment supply, sediment availability, and transport capacity controls the magnitude, frequency, and intensity of dust storms [*Bullard*, 2013]. Distinct seasonalities to dust storm frequency in subtropical dust sources are primarily controlled by seasonal variations in wind regimes (both wind speed and direction). The controls on dust storm seasonality in high latitudes are arguably more complex due to the very close coupling between sediment supply and dust emissions with often a limited time period when sediments are available and wind regimes conducive to entrainment from dust sources. In many high-latitude dust areas, air temperature affects glacial meltwater discharge and consequently suspended sediment yield. Interannual variation in meltwater suspended sediment yield is very variable at high latitudes [e.g., *Hodgkins et al*., 2003] and has a nonlinear relationship with discharge. For the same discharge, suspended sediment yield can be higher during the spring and lower in the autumn due to seasonal exhaustion

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Table 2. A Comparison of Some Key Characteristics of High-Latitude Dust Sources

	Alaska	Canada	Greenland	Iceland	Antarctica	New Zealand	Patagonia
Area of active dust emission	No data available	No data available	No data available	20,000 km^2 (area with active aeolian processes)	4,800 km^2 (area of Dry Valleys)	34,300 km^2 (area susceptible to wind erosion)	527,000 km^2 (Patagonian steppe)
Key known locations	South central and south west including Copper River and Matanuska-Susitna Valley	Isolated locations in the Yukon, Baffin Island, and Ellsemere Island	Kangerlussuaq Fjord region and ice-free northern land mass	Southern coast and North East	McMurdo Dry Valleys	Lake Tekapo region, South Island	Provinces of Chubut (e.g., Lago Colhué Huapi); Santa Cruz and Tierra del Fuego
Geomorphology of dust sources	Glacial outwash plains, braided river systems, and reworked loess	River floodplains and glacial outwash	Glacial outwash plains and reworked loess	Glacial outwash plains	Dry river valleys and lake beds and debris bands in ice	Braided river systems and reworked loess	Alluvial fans, dry or ephemeral lakes, braided riverbeds, former glacial outwash plains, and reworked loess
Key dust-raising wind systems	Katabatic winds	Chinook/föhn winds and katabatic winds	Katabatic winds	Low-pressure systems and katabatic winds	Katabatic winds	Föhn winds	Regional southwesterly winds and katabatic winds
Threshold wind speed	$>14\ m\ s^{-1}$ at 2 m	$2.5\ m\ s^{-1}$ at <0.5 m	$6\ m\ s^{-1}$ at 2 m	$5–10\ m\ s^{-1}$ at 2 m	Unknown	$7.5\ m\ s^{-1}$ at 2.65 m	Unknown
Seasonality of emissions	Primarily autumn	Late winter/early spring and autumn	Spring and autumn/winter	Year round but dominate in spring and early summer	Winter (all aeolian activity)	Early spring (September and October) and late Autumn (April and May)	Spring (October and November)-late summer (March and April)
Quantity of emissions	$>0.06 \times 10^6\ t\ yr^{-1}$	No data available	No data Available	$35 \pm 5 \times 10^6\ t\ yr^{-1}$	No data available	No data available	$30 \times 10^6\ t\ yr^{-1}$
Mean annual rainfall at dust sources	$200–450\ mm\ yr^{-1}$	No data available	$<200\ mm\ yr^{-1}$	$1500–2500\ mm\ yr^{-1}$	$3–50\ mm\ yr^{-1}$	$600\ mm\ yr^{-1}$	$<300\ mm\ yr^{-1}$

of sediment supplies [*McDonald and Lamoureux*, 2009]. Discharge is closely linked to the magnitude of seasonal snowmelt even in catchments dominated by ice sheets [*Chu et al*., 2009; *Lawler et al*., 2003]. As a consequence of the way in which these different variables combine, seasonality of dust emissions can vary from source to source (Table 2). In some areas, early spring season meltwater containing high concentrations of suspended sediment can replenish floodplains. Given a lack of, or limited snow cover, these sediments can be deflated to produce spring dust storms as in Iceland, New Zealand, and Alaska. Where snow cover persists for longer and/or a second pulse of sediments is delivered to the floodplain at the end of the summer, the main dust storm season (e.g., Alaska) or a second weaker dust season (e.g., New Zealand and Canada) occurs during the autumn months. In Alaska, snow accumulation in winter and temperatures in the summer are good predictors of dust activity in the autumn. Strong winds may serve to increase dust storm magnitude and/or frequency during winter months in Canada and Greenland.

Several factors limit field studies of dust emission in high-latitude regions. These factors include remoteness, very low temperatures, snow and ice cover, and lack of daylight during winter months and mean that there have been very few year-round field studies of dust emissions in these regions. As with many subtropical dust source areas, the low densities of population (typically $<0.5\ \mathrm{km}^2$ outside cities) and of meteorological stations mean that many small-scale ephemeral events go unobserved. In some cases this may be due to the vastness of the uninhabited areas of the northern Arctic and Antarctica; in other cases it may be that dust was detected but not attributed to local sources due to lack of awareness of dust originating from high latitudes. For example, while reexamining data collected in North Canada during the 1970s and 1980s [*Barrie*, 1986; *Barrie and Barrie*, 1990] for a study on intercontinental aerosol transport, *Fan* [2013] noted an unexplained increase in dust observations at Alert, Canada (82°30′05″N, 62°20′20″W) during the fall months. It is likely that the fall peak at Alert and at other locations in Alaska was caused by local dust entrainment [*Polissar et al*., 1998; *Stone et al*., 2014].

5.2. Challenges of Satellite Remote Sensing of High-Latitude Dust

A sparse population and low density of meteorological stations are also characteristics of many subtropical dust source areas, but here this limitation has largely been overcome through the use of satellite remote sensing data. These have provided a rich source of information on the spatial distribution and temporal cycles of dust storms at regional to near-global [*Prospero et al*., 2002; *Washington et al*., 2003; *Ginoux et al*., 2012] and subcatchment scales [e.g., *Bullard et al*., 2008; *Lee et al*., 2009]. Although there are limitations with some of these satellite-derived data sets, such as difficulty detecting dust plumes over some surface types [*Baddock et al*., 2009], they have provided genuine insights into subtropical dust storm dynamics and dust pathways.

Satellite detection of dust is a useful tool for assessing the extent of a dust event and source location, but its application is particularly challenging in the high latitudes. First, there are long periods of darkness above the polar circles (66°33′N/S) in late fall and winter that limit the use of passive remote sensing, which is reliant on reflected sunlight, as a year-round tool. Second, cloud cover is far greater at high latitudes than in the subtropics, especially during the nonwinter months, such that the presence of cloud can obscure dust plumes and confound the performance of dust retrieval algorithms. For example, in the Northern Hemisphere July cloud cover at high latitudes is 70–80% compared with 10–20% in the subtropics; in the Southern Hemisphere cloud cover is 70–80% during the summer (January) compared with 30–40% January cloud cover in the subtropics [*NASA*, 2014]. In the subtropics dust activity is known to be marginally underrepresented in satellite retrievals when events occur during the night or under cloudy conditions [*Prospero et al*., 2002; *Ginoux et al*., 2012], but the combined effect of long dark winters and frequent cloud cover during the summer magnifies these problems in high latitudes. Even in high-latitude areas that receive several hours of daylight during the winter months, for example, Patagonia, the low-pressure systems that trigger the intense winds associated with dust uplift in this region also bring abundant cloudiness, making consistent remote sensing of dust activity difficult.

Active remote sensing approaches using depolarization such as Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) [*Winker et al*., 2003] or Cloud and Aerosol Transport System (CATS) [*McGill et al*., 2015] are highly effective as they not only identify whether sensed aerosols are likely to be dust or not but also detect dust as a function of height during daytime and nighttime (Figure 19). However, the period between revisits of these sensors over the same dust-bearing area is lengthy, and given that the chance of cloud obstruction is very high for each overpass, effective capture of high-latitude dust events is

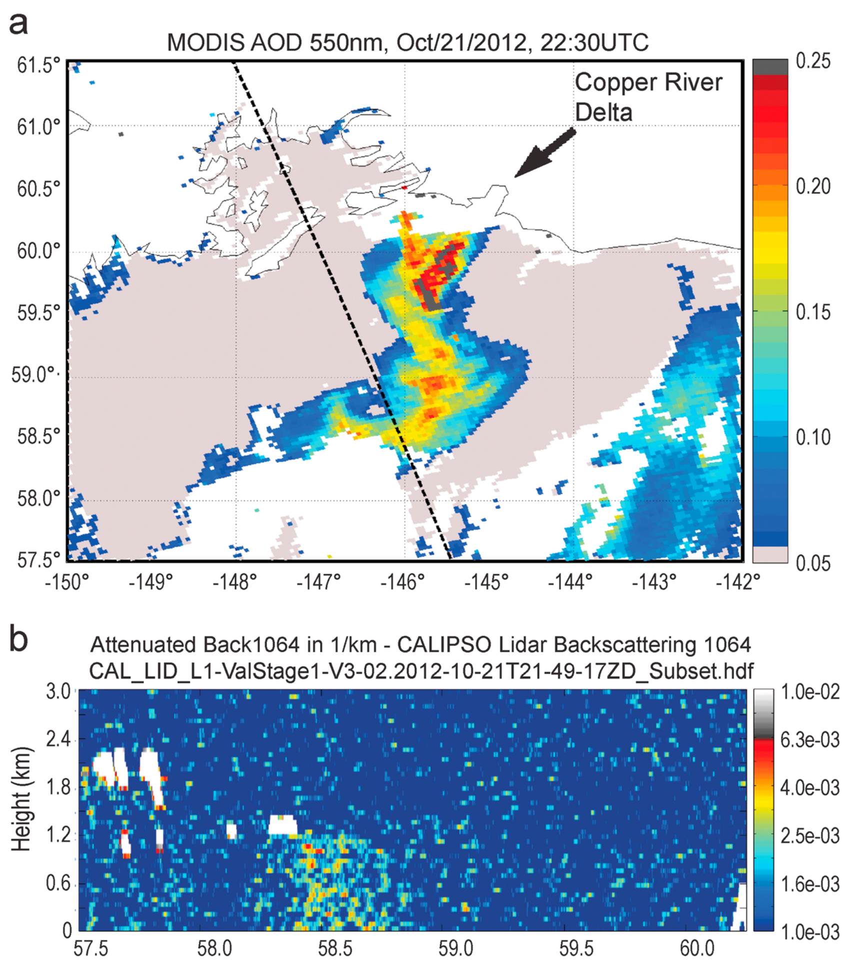

Figure 19. (a) Aerosol optical depths (a proxy for aerosol concentration) derived by the satellite detector MODIS of a dust event in Alaska on 21 October 2012. Dust is blown out from the Copper River Delta into the Gulf of Alaska (only sectors with aerosols detected by the satellite are shown). The black dashed line is the track of an almost simultaneous overpass of a spaceborne lidar (CALIOP). (b) The respective profile of the attenuated backscattering coefficient at 1064 nm (another proxy for aerosol concentration). The sector between 58.25°N and 59°N shows the dust cloud confined to the marine boundary layer (bottom 1.2 km).

serendipitous. This means that characteristics like dust plume height are only infrequently available. Multiangle Imaging Spectroradiometer (MISR) [*Kahn and Gaitley*, 2015], Advanced Along Track Scanning Radiometer [*Curier et al.*, 2009], Polarization and Directionality of the Earth's Reflectances (POLDER) [*Hasekamp et al.*, 2011], or ultraviolet range observations from Ozone Mapping Instrument (OMI) [*Levelt et al.*, 2006] have been proven useful at identifying dust at low latitudes but have some deficiencies that become apparent at high latitudes. For example, sensors such as OMI and POLDER have large ground pixel resolution and suffer from pervasive cloud contamination; MISR and the lidars CATS and CALIOP have a narrow instrument swath which means effective revisits to the same area are infrequent.

Geostationary satellites can overcome some of the difficulties associated with a low number of repeat observations. The GOES satellite series has good coverage of high latitudes to approximately 60°N and S—these satellites are stationed over the equator at 36,000 km distance while polar satellites fly at 700 km. GOES is very effective for monitoring dust activity in Patagonia, and there is good coverage of the Gulf of Alaska, Southern Greenland, and Iceland particularly in the summer months. However, although the spatial coverage is adequate, GOES sensors are not very good at quantitative retrievals of dust due to the lack of adequate wavelengths for performing such a task. New generations of satellites should offer additional capabilities for studying high-latitude dust. For example, the recently deployed satellites Himawari-8 and the Second

Generation Meteosat have sensors with high spatial resolution, the appropriate channels for dust detection (especially over the ocean) and coverage of different high-latitude regions, potentially overcoming some of the limitations noted for the polar sensors.

Clear skies are not the only prerequisite for dust detection. It is also important to establish whether observations made are of mineral dust or other aerosols. Fortunately, most high-latitude dust is produced in clean environments where the dominant aerosols are background continental, marine, and occasionally smoke aerosols. This is not the case in many low-latitude dust source regions such as central and SE Asia or the Sahel in Africa. Strong absorption of blue light means that true color satellite imagery can be effective in identifying dust, especially over dark oceans (e.g., Figure 12). Over high albedo surfaces such as snow and ice, however, visual identification of suspended dust that relies on visible wavelengths is less effective. This condition is analogous to some degree with the difficulties of identifying dust over bright desert surfaces [*Baddock et al*., 2009]. Some methods for enhancing the appearance of dust in satellite imagery take advantage of the thermal contrast between a warmer land surface and the cooler temperature of dust plumes that are in suspension. In high latitudes with generally colder land surfaces, there is less of a contrast between the surface and elevated dust, however, and certain enhancement approaches found to be effective in warm desert environments are less useful over colder lands [*Miller*, 2003].

Postprocessed satellite data products are now available globally in many forms, and for aerosol studies, estimates of the total concentration of dust in the atmospheric column as expressed by the aerosol optical depth (AOD) are useful for quantifying the distribution of dust. Climatologies of the spatial and temporal variability of dust based on AOD have been successfully developed for subtropical desert regions and have elucidated many large-scale controls on dust emission [e.g., *Ginoux et al*., 2012] and transport pathways [*Kaufman et al*., 2005]. Unfortunately, the application of products like AOD is less straightforward in high latitudes. In many instances, where dust may well be apparent in the visible images captured by a satellite, retrievals of AOD might be lacking for the same scene. Many of the conditions required by automatic detection algorithms to successfully identify aerosols and return accurate AOD (e.g., degree of cloudiness in a pixel, viewing angles, homogenous dark surface, moderate to high aerosol concentrations, and number of views per day) are not fulfilled poleward of 45–50° latitude, which reduces the extent and frequency of AOD retrieval in those regions.

There are also a number of artifacts in high-latitude remote sensing of dust that arise from the most commonly used satellites and sensors aligned on polar-orbiting paths [e.g., MODIS sensor on board the Terra and Aqua spacecraft). In low latitudes, the issue of satellite overpass times leading to failures in the detection of dust events is well known [*Schepanski et al*., 2009]. The inclination of the Terra and Aqua satellites (one is ascending and the other is descending) results in frequent but grouped overpass timings at high latitudes. This can mean that there is an increased chance of missing dust events in these environments. The Terra and Aqua imagery used by *Thorsteinsson et al.* [2011] over Iceland was taken at 1330 and 1350 UTC respectively, whereas in equatorial regions the separation of the two MODIS overflights is approximately 3 h. Such short observation intervals at high latitudes also mean that the timespan over which the evolution of dust plumes can be monitored using differently timed images is reduced. In summer seasons, however, the convergence of polar-orbiting satellite tracks at high latitudes leads to the potential for additional satellite coverage and imagery for a given dust event day. For example, north of 58°, almost any given sector is observed twice by MODIS bringing the number of daytime observations to four. This increases the chance of observing a clear-sky pixel or permitting the study of the evolution of a dust cloud. Satellite data algorithms that have been developed for aerosol and dust detection are typically optimized for performance in the global dust belt associated with low latitudes. Due to the satellite geometry of high latitudes, sensor viewing angles and off-nadir pixel resolution can be increased, especially at the extremity of scenes, and this has effects on dust retrievals and spatial resolution. For assessments of high-latitude dust based on AOD, contributions from maritime aerosols (e.g., sea salt) can be confounding, as values around 0.06 can be attributed to nonaeolian dust [*Kaufman et al*., 2005]. While less of an issue for source detection and AOD quantification over inland, moderate to high-intensity dust sources at low latitudes, proportionally, this error is more significant in less intense, commonly coastal, high-latitude source areas.

These issues associated with high-latitude remote sensing mean that there has been an absence of systematic high-latitude dust studies or remote sensing-based climatologies of dust. As noted by *Tomasi et al.* [2015], until more sophisticated aerosol detection algorithms are implemented and new instruments are deployed with features that overcome the problems mentioned above, systematic remote sensing of aerosols in the polar regions in general and in particular aerosol identification (in this case dust) is not currently possible. While not a dedicated high-latitude remote sensing dust monitoring study, *Kaufman et al.* [2005] is one of the few studies that presents multiyear AOD from MODIS as far north as between 50° and 60°, revealing peaks in this value during April for the region 10°–20°W. This is an ocean region known to be under a transport pathway for dust sourced from southern Iceland, and the peak agrees with known timing of dust activity (section 4.4).

5.3. Quantifying High-Latitude Dust Emissions

The entrainment, transport, deposition, and impacts of dust in the earth-atmosphere-ocean system depend on surface fluxes, i.e., the exchange of energy, momentum, and matter among these components. These include both material fluxes (e.g., moisture and aerosols) and turbulent fluxes (e.g., wind stresses and heat fluxes). The frequency, accuracy, and spatial resolution of measurements of these fluxes have to be appropriate to the spatial and temporal scale of the component of the dust cycle under investigation [*Shao et al*., 2011].

As discussed in section 3, a number of environmental drivers of dust entrainment processes at high latitudes do not occur, or occur to a far lesser extent, in the subtropics. Consequently, an understanding of physical processes operating at low latitudes may not fully explain those observed at high latitudes. It is therefore important to undertake measurements of high-latitude dust entrainment processes and fluxes in the field as well as in appropriately calibrated wind tunnels [*McKenna Neuman*, 2004]. Unlike subtropical dust source regions, those in high latitudes often have very low winter temperatures, the presence of ice and deep, often drifting snow, and extremely high wind speeds. In order to capture year-round in situ data quantifying meteorological conditions and sediment fluxes, it is necessary to use instruments that will function during long periods of low temperatures and polar darkness, can withstand icing, and are reliable in locations often very far from support services [*Palecki and Groisman*, 2011; *Bourassa et al*., 2013]. The harsh conditions during high-latitude winters can also pose serious challenges to researchers [*Kadir et al*., 2013] making it preferable to use self-logging instruments that can be installed at site and downloaded remotely or manually after extended intervals rather than requiring daily servicing.

Most instruments used in dust research are designed for, and have only been tested in, temperate and subtropical conditions. For example, there are numerous different types of dust trap used to sample wind-blown particles; these can be categorized as either active or passive samplers. An active sampler is furnished with a pumping device to maintain a constant flow of air through the intake. This means that it requires a reliable and continuous source of power. Passive samplers depend on the local wind to drive air through the device. As passive samplers are cheap and require no power supply, they are widely used. One of the most common samplers for field measurements is the BSNE (Big Spring Number Eight) trap [*Fryrear*, 1986]. Wind tunnel experiments indicate that the BSNE has a sediment trapping efficiency of 40% [*Goossens and Offer*, 2000]. While the trapping efficiency varies with particle size [*Shao et al*., 1993], a genuine advantage over other samplers is that the efficiency of the BSNE is invariant with wind speed as tested at speeds from 1 to 5 m s^{-1} [*Goossens and Offer*, 2000]. There has been no study into how the efficiency of this trap (or other dust samplers) may vary at higher wind speeds such as those more typical of many high latitudes. Nonetheless, the BSNE has been used for field studies at high latitudes in Iceland [*Arnalds et al*., 2012] and in Greenland by *Bullard and Austin* [2011] who added a rain/snow hood to the original design [*Shao et al*., 1993]. The disadvantage of the BSNE and other passive traps is that the temporal resolution of the data usually depends on manual emptying of the trap which does not make it appropriate for long-term studies where researchers are not on site. To address this, in Antarctica, *Gillies et al.* [2012, 2013] successfully deployed for 1 year a modified BSNE-style trap with the capability to open and close the sampling orifice and log the elapsed time, thus allowing a time-resolved flux to be calculated.

Active samplers have been used for collecting aerosols, including dust, at some remote high-latitude sites. Most of these deployments have been associated with short field campaigns and so provide discontinuous data [e.g., *Dibb*, 2007]. In order to obtain sufficient sample mass for detailed analysis, sample integration times are typically as long as 3–4 days [*Colin et al*., 1997; *Hagler et al*., 2007] which makes it challenging to differentiate the precise timing of dust events. More recently, *VanCuren et al.* [2012] developed a bespoke active sampler that they successfully used to capture a continuous record of aerosols at Summit, Greenland (72°N, 38°W). The sampler was configured to run unattended for 48 weeks continuously collecting particles in 8 size bins (from 0.09 μm to 10 μm aerodynamic diameter). Due to mechanical difficulties, only 170 days of data were captured but included both summer and winter seasons. This instrument demonstrates potential for future year-round high temporal resolution sampling at high latitudes [*VanCuren et al*., 2012].

Regional-scale estimates of fluxes are often inferred using measurements from instrument networks, for example, from meteorological stations (as in Figure 3) or ground-based aerosol sensor networks such as Aerosol Robotic Network (AERONET) and SKYNET [*Tomasi et al*., 2015]. Such instruments must be accurate and reliable to ensure quality and completeness of data and must also be robust enough to understand the rigors of harsh winters at high latitudes. At high latitudes, although the instruments themselves can often operate in extreme conditions (e.g.,−49°C recorded in Barrow, Alaska, in 2006), they may require custom engineering to mount and power the instruments and despite combined power systems (solar, wind, and cold weather-tolerant batteries) there can still be considerable challenges of ensuring data continuity during long, cold, dark winters [*Palecki and Groisman*, 2011]. Other challenges of autonomous instrument networks include drifting snow that can make year-round observations of near-surface measurements difficult. Improvements in telemetry do now permit remote downloading of data from isolated stations but this can be expensive.

Notwithstanding these challenges, some regional networks of stations do exist and provide data that can be used to quantify high-latitude dust to some extent. One example is the world meteorological station network that records visibility, as utilized to produce Figure 3. Meteorological stations often record dust codes that indicate the timing and severity of dust events which have been combined with visibility information to estimate dust storm frequency and intensity at low latitudes [e.g., *Middleton*, 1984; *McTainsh et al*., 1990; *Lim and Chun*, 2006]. They have been used here to produce Figures 10 and 14. There are a number of limitations to the use of dust codes [*O'Loingsigh et al*., 2010], but the widespread distribution, and often long records, held by meteorological stations may outweigh these. Meteorological data are available from local stations and from online databases such as that hosted by the National Oceanic and Atmospheric Administration (https//www.ncdc.noaa.gov). Other online data sets are available via EBAS (http://ebas.nilu.no) and the NOAA Earth System Research Laboratory (www.esrl.noaa/gov) both of which include aerosol data. The challenges with obtaining regional estimates of dust emissions from these data sets include reconciling the differences between different instruments and observers and obtaining sufficiently detailed information to be able to differentiate locally derived mineral dust from other aerosols such as far-traveled dust, sea-salt, anthropogenic aerosols (e.g., black carbon) and Arctic haze.

5.4. High-Latitude Dust in Global Dust Models

Most of our large-scale understanding of the dust cycle comes from global dust models that include dust emission, transport, and deposition schemes based on parameterization of processes observed in field studies and tested against natural dust archives such as marine and ice cores and terrestrial sedimentary records [e.g., *Albani et al*., 2015]. The basic structure of global dust models is via a series of horizontal cells at resolutions of ~0.5° to 5° and 20–60 vertical layers with a dust emission scheme that simulates dust aerosols in various size ranges [*Huneeus et al*., 2011]. Global dust models are designed to quantify global, regional, and seasonal variations in dust loads. The estimated total contemporary global dust load is typically 1000–2000 Tg yr^{-1}. Variations in this value are often attributed to how sources and sediments are parameterized [e.g., *Uno et al*., 2006; *Yin et al*., 2007] and assumptions about the dust emission and deposition schemes [*Textor et al*., 2007; *Huneeus et al*., 2011]. The importance of surface conditions for model performance is demonstrated by the improvements in earlier modeling outputs that resulted from the inclusion of preferential source areas in descriptions of the land surface [*Ginoux et al*., 2001; *Zender et al*., 2003].

Until recently, global dust models did not include glacigenic dust sources, including those at high latitudes, even for simulating aerosol concentrations during dustier climate periods such as the LGM. During the LGM ice covered around 25% of Earth's land area and potential dust source areas were considerably more extensive in both the Northern Hemisphere, where they were generally associated with maximum ice limits [*Mahowald et al*., 1999], and the Southern Hemisphere where glacigenic dust sources were more prevalent in South America and greater aridity promoted dust emissions in Australia and southern Africa [*Hall*, 2004]. Without explicitly taking into account glacigenic sources, *Mahowald et al.* [2006] suggest that the total global dust source area at the LGM was up to 35% larger than at present (based on vegetation cover and CO_2 fertilization effects) with total dust loadings up to 60 Tg m^{-2}. When selected glacigenic dust sources in Europe, Siberia, North America, and the Pampas region of South America are factored in, modeled global dust loadings for the LGM are predicted to have been 70–80 Tg m^{-2} demonstrating their importance to the overall budget.

Under contemporary conditions, models suggest that the dust emission rates from South America are 35–45 Tg yr^{-1} [*Zender et al*., 2003; *Tanaka and Chiba*, 2006], but this estimate does not differentiate high latitude (i.e., southern South America ≥40°S) from more northern sources. The compilation in Table 2 suggests that high-latitude dust emissions from Patagonia are ~30 Tg yr^{-1}. Icelandic dust emissions are estimated at 35 ± 5 Tg yr^{-1}, with a minimum annual emission rate from Alaska of $>0.06 \times 10^6$ Tg yr^{-1}. There are no estimates of dust emissions for the other high-latitude dust sources, but conservatively, we suggest that in total, globally, they might contribute at least 80–100 Tg yr^{-1} to the global dust cycle. This estimate is considerably higher than most model estimates of emission rates from North America (excluding Alaska and Canada; 2–53 Tg yr^{-1}), a similar order of magnitude to that from southern Africa (63 Tg yr^{-1}) and within the range suggested for Australia (37–148 Tg yr^{-1}) [*Bullard*, 2011; *Shao et al*., 2011]. Calculations of global dust emissions are very variable, but estimates of the amount entering the atmosphere each year converge around 2000 Tg [*Bullard*, 2013] which suggests that high-latitude sources contribute approximately 5% of the global dust budget.

There are a number of challenges to incorporating contemporary high-latitude dust emissions into global dust models. One of the most important is the scale of the models as their typical degree-scale grid resolution renders them too crude for smaller-scale enquiries. Unlike subtropical dust sources which can be extensive, many high-latitude dust sources are relatively small and discrete and therefore below the spatial scale that can realistically be parameterized within the models. Equally important is the challenge of modeling wind fields at appropriate scales. Field studies suggest that katabatic winds are crucial for aeolian entrainment in some high-latitude regions. Katabatic winds are rarely incorporated into global models because the grid size prevents the simulation of such small-scale phenomena [*Moore et al*., 2015; *Oltmanns et al*., 2014] although they have been included with some success in regional climate models [*Jourdain and Gallée*, 2011]. Wind gustiness is also excluded from most models despite its importance for dust emissions [*Engelstaedter and Washington*, 2007].

More broadly, the feedback role of high-latitude dust in global climate models is poorly understood. Although modern high-latitude dust activity can be intense, it is typically limited to short timespans (a few days-weeks per season) and does not appear to travel long distances at high concentrations. These two features suggest that the direct (i.e., blocking sunlight) radiative forcing of modern high-latitude dust is a minor component in the annual global radiation budget, particularly when compared to its effects during glacial periods when global atmospheric dust loadings were 2 to 20 times current amounts [*Lambert et al*., 2008; *Albani et al*., 2015]. Dust in the atmosphere also has potential indirect effects on radiative forcing [*Lohmann and Feichter*, 2005], but the specific contribution of dust from high-latitude sources is unknown. It is known that dust provides nuclei for ice and droplet formation in clouds [*Atkinson et al*., 2013] and that natural mineral aerosol is the important source of ice nuclei for colder temperatures (compared to biological sources which are more important at warmer temperatures) [*Bromwich et al*., 2012]. High-latitude dust, particularly in the Northern Hemisphere, tends to travel at or below cloud level and may impact cloud properties, particularly in mixed-phase clouds [*Lohmann and Diehl*, 2006]. Investigations of the effect of mineral dust aerosols on clouds in polar regions have tended to focus on dust sources from Asia and the Sahara in the Arctic [*Fan*, 2013; *Breider et al*., 2014] and from Australia and South America in Antarctica [*Bromwich et al*., 2012], and the impact of dust sources from within the high latitudes has yet to be assessed. The effect of nutrient deposition on marine biota and subsequent climate biofeedback [*Mahowald et al*., 2011] also has yet to be evaluated for high-latitude dust sources. Simulations of the radiative forcing of dust and black carbon in seasonal snow in North China suggest that the magnitude of radiative warming in the snowpack is comparable to the magnitude of surface radiative cooling due to black carbon and dust in the atmosphere [*Zhao et al*., 2014].

5.5. Future Prospects and Opportunities for High-Latitude Dust Research

An important conclusion to be drawn from this study is that understanding high-latitude dust in the Earth system, even at relatively small scales, requires a multidisciplinary approach combining expertise in geomorphology, glaciology, meteorology, oceanography, sedimentology, atmospheric sciences, and other specializations. It also requires the use of a range of research tools including fieldwork, experimentation, observational networks, remote sensing, and modeling.

A distinctive feature of high-latitude dust sources is that they are located in paraglacial environments. Paraglacial environments respond strongly to large-scale external climate forcing and are sensitive to climate changes associated with glacial-interglacial fluctuations and are also expected to be sensitive to future enhanced global climate change [*Mercier*, 2008; *Knight and Harrison*, 2009]. Many glaciers have been retreating over recent decades; for example, during the twentieth century all glaciers in Iceland have retreated [*Björnsson and Pálsson*, 2008] and high-latitude glaciers and ice sheets are expected to retreat further during the 21st century [*Radić et al*., 2013; *Clarke et al*., 2015]. Glacier retreat is anticipated to expose large source areas of dust associated with glaciofluvial sediments. In some regions sediment supply, coupled to ice sheets and glaciers, to high-latitude dust sources via meltwater systems and outwash plains may increase over the short term (decades) [*Jansson et al*., 2005; *Bliss et al*., 2014] but the overall relaxation time in different landscapes will vary. Countering this, factors that decrease sediment availability such as vegetation growth or colonization [e.g., *Klaar et al*., 2015] or the development of proglacial lakes may cause a rapid decrease in sediment availability to the aeolian system [*Bullard*, 2013].

These changes and the preceding evaluation of existing research suggest that a wide range of research questions still need to be tackled to fully understand the drivers, roles, and importance of high-latitude dust in the Earth system. At the process scale, very little work has been undertaken to determine how dust entrainment and emission at high latitudes differs from that in the subtropics. While research on the behavior of sand-sized material in cold climates has been conducted, reviewed, and is ongoing [*McKenna Neuman*, 1993, 2003], insights gained from this research have been applied to, but not tested on, fine particles. In the context of understanding the origins of loess, some experiments have examined the production of fine particles by aeolian abrasion of glacial sediments [*Smith et al*., 1991]; however, the impact of air temperature on the rate of abrasion has not been explored. Both aeolian abrasion [*Smith et al*., 1991; *Bullard et al*., 2004] and frost weathering [*Wright et al*., 1998] are known to contribute independently to the production of fine particles (silts and clays). Moreover, aeolian abrasion may occur more rapidly in cold than in temperate or warm environments due to increased particle brittleness caused by weakening of microfractures [*Moss and Green*, 1975].

As highlighted in section 5.3, field measurements of high-latitude dust can be logistically challenging. To date, most research has been event based or focused on short, summer seasons. A key goal for the subdiscipline must be to obtain detailed year-round measurements of dust flux and deposition concomitant with high-resolution meteorological data. An integrated dust observation network across the high latitudes would provide valuable data to assist in quantifying the magnitude and frequency of dust events. Technological advances are improving automated instruments that can be used to quantify dust, and the ability to download data from remote areas via satellite will both help to overcome temporal sampling and access issues. Such a network of stations would be very valuable, but field- or plot-scale research (10^{-2} to 10^{2} m) is also required to evaluate the impacts of spatial variability in sediment supply, redistribution of sediments. and snow by winds, and the role of surface and near-surface microclimate on dust emissions. One possible way to further increase the density of dust observations could be through the establishment of community dust monitoring and reporting networks [*Leys et al*., 2008]. Although the population of many high-latitude dust source regions is sparse, numbers are growing. For example, the population of Alaska has increased by 17% and of Iceland by 15% since 2000 with most population growth concentrated on larger settlements. Both the greater Anchorage area, Alaska, [*Department of Labor and Workforce Development*, 2014] and Reykjavík, Iceland, [*Landshagir*, 2015] have predicted population increases over the next few decades, and both areas are vulnerable to dust storms that decrease air quality. Consequently, more research into the effects of local dust storms on human health in cold environments may be welcomed.

For each high-latitude dust region, with the exception of Iceland, large gaps still exist in our understanding of some of the basic characteristics of the dust sources (Table 2). These include a quantification of the areal extent of dust sources, comparable information concerning the wind thresholds required to entrain dust, and, importantly, estimates of total annual dust emissions from each region. Our first estimate (section 5.4) is that under contemporary environmental conditions 80–100 Tg yr^{-1} of dust is contributed to the global dust cycle from high-latitude sources; this represents up to 5% of the global dust budget. Considerably more field data and modeling efforts are required to test the robustness of this value.

Glossary

ATSR the Along Track Scanning Radiometer is a multichannel radiometer providing information about vegetation, sea surface temperature, and clouds/precipitation. The ATSR instruments are onboard European Space Agency satellites (ERS-1 and ERS-2).

Aeolian wind activity which shapes the surface of the Earth, through erosion, transport, and deposition.

AERONET the AERONET (Aerosol Robotic Network) program is a federation of ground-based remote sensing aerosol networks that provides a public domain database of aerosol optical, microphysical, and radiative properties.

Albedo the reflectivity of a substance expressed as the ratio of reflected radiation to total incident radiation (usually referring to the visible wavelengths). It can vary depending on the optical properties of the surface, the surface roughness, and the angle of incoming radiation. Dry snow is highly reflective and has a very high albedo (0.80–0.97), whereas even clean glacier ice has a much lower albedo (0.35–0.55). This is because glacier ice is crystalline, with a surprisingly rough surface, and contains impurities such as gas bubbles and liquid water pockets, all of which scatter light and decrease albedo. Particulate matter falling on the ice surface decreases reflectance further, depending on the darkness and surface roughness of the material. Consequently, dust-covered dirty ice can have a very low albedo (0.10–0.25).

AOD aerosol optical depth is a measure of aerosols (including dust, sea salt, and smoke) within the atmosphere. It is a dimensionless number related to the amount of aerosol in the vertical column of atmosphere over a location.

CALIOP the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) provides high-resolution vertical profiles of aerosols and clouds and is an instrument mounted on the CALIPSO satellite.

CATS the Cloud and Aerosol Transport System (CATS) is a NASA lidar remote sensing instrument that extends profile measurements of atmospheric aerosols and clouds from the International Space Station.

Cold climate where mean annual air temperature $< +3°C$ and the coldest mean monthly temperatures are $< -3°C$.

Dust fine particulate matter, which can be transported over large distances by aeolian suspension.

EPA United States Environmental Protection Agency: A federal government agency which was formed to protect the environment and human health, by writing and enforcing regulations based on laws passed by the U.S. Congress.

Foehn/föhn/Chinook winds occurring in the lee side of a mountain range; these are dry, warm, downslope winds. This type of wind has many local names including Chinook wind in north America where various mountain ranges meet the Canadian Prairies and the Great Plains, föhn in the Alps region of Europe, and zonda in Argentina.

GEOS the Geostationary Operational Environmental Satellite (GOES) program comprises a series of geostationary satellites (always in the same position with respect to the rotating Earth) that carry instruments for meteorology and for monitoring dust storms, volcanic eruptions, and forest fires.

GRIP the Greenland Ice Core Project organ traveled through the European Science Foundation which successfully drilled a >3000 m ice core from Summit, in the center of the Greenland ice sheet to the bed (72°35′N, 37°38′W)

HNLC regions of the oceans that have high nutrients and low-chlorophyll, owing to limited concentrations of metabolizable iron. Approximately 20% of the world's oceans are HNLC, including the equatorial Pacific Ocean, subarctic Pacific Ocean, and the Southern Ocean.

Katabatic winds winds which originate from the high elevations of mountains, plateaus, glaciers, and flow downslope under the influence of gravity. They are often caused by surface cooling at night.

Loess windblown sediment which has been deposited and loosely compacted. It is estimated to cover up to 10% of the terrestrial globe.

MISR Multiangle Imaging Spectroradiometer is a scientific instrument on board the NASA Terra satellite. MISR views the Earth simultaneously at nine widely spaced angles which makes it possible to distinguish different types of atmospheric particles, cloud forms, and land surface covers.

MODIS the Moderate Resolution Imaging Spectroradiometer; a scientific instrument on board the NASA Terra (launched 1999; morning overpass) and Aqua (launched 2002; afternoon overpass) satellites. MODIS data have extensively been used to track and map dust storms.

Niveo-aeolian processes the transport and deposition of mixed sediments and snow which can occur when wind erodes snow cover down to exposed underlying sediments that are also then deflated or during simultaneous dust and snow storms. Some niveo-aeolian deposits are ephemeral due to seasonal melting of snow; others are longer lived.

Paraglacial Vegetation-free landscapes which have been exposed following glacier retreat/deglaciation, causing unstable conditions.

pCO_2 partial pressure of carbon dioxide.

Periglacial used to describe cold, nonglaciated environments where geomorphic processes and landforms are dominated by repeated freezing and thawing.

Permafrost ground which remains frozen for all or a large part of the year and is mainly located in the Polar Regions.

POLDER Polarization and Directionality of the Earth's Reflectances is a passive optical imaging radiometer and polarimeter developed by the French National Centre for Space Studies CNES.

Proglacial a feature which is in front of, beyond, or at the margin of a glacier or ice sheet.

PM_{10} particulate matter up to 10 μm in diameter.

$PM_{2.5}$ particulate matter up to 2.5 μm in size.

Sandur an outwash plain formed by glacial meltwater.

SKYNET is an observation network that monitors optical and microphysical properties of aerosols, clouds, and atmospheric radiation.

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